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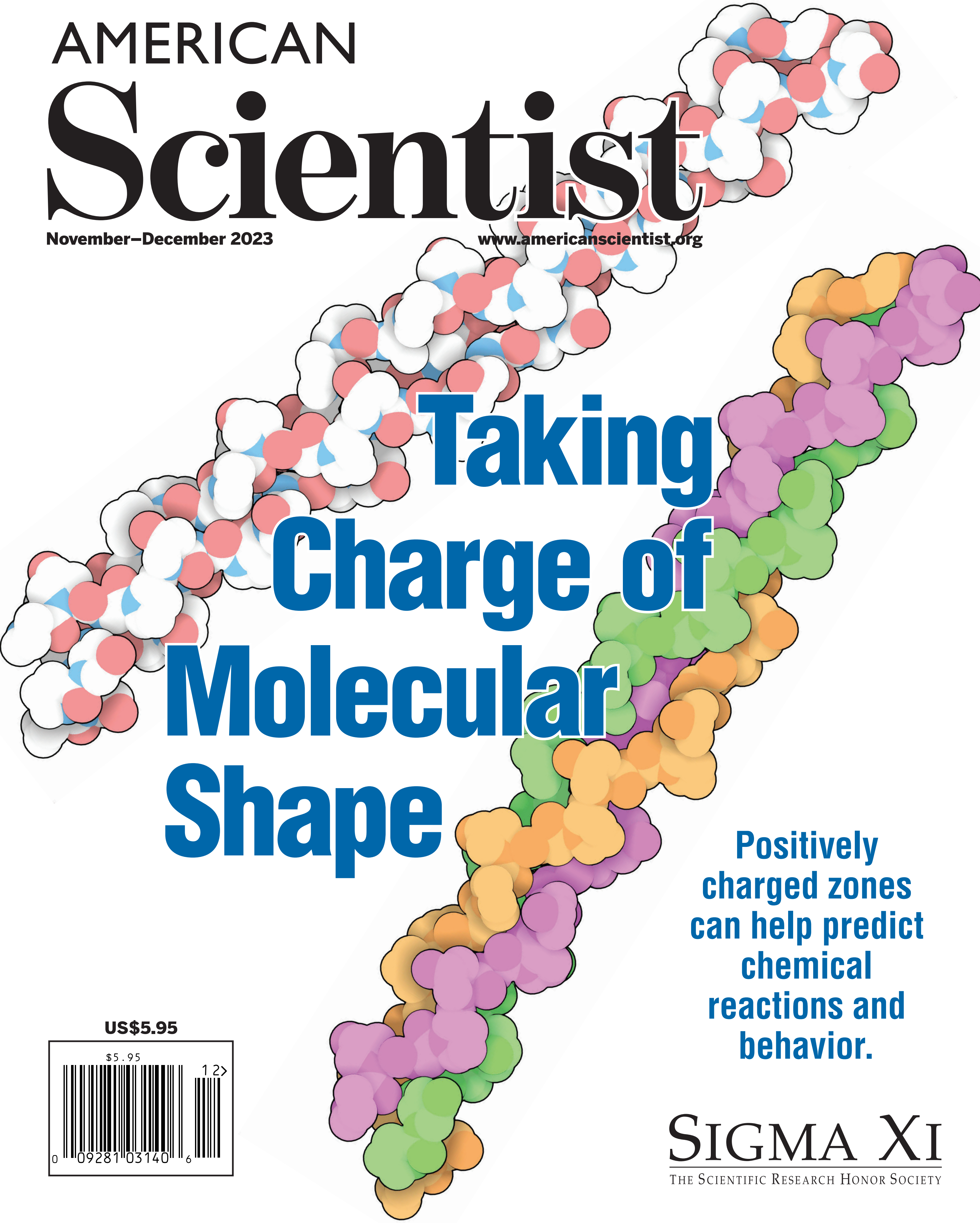

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# Sacred Stone of the Southwest is on the Brink of Extinction

Centuries ago, Persians, Tibetans and Mayans considered turquoise a gemstone of the heavens, believing the striking blue stones were sacred pieces of sky. Today, the rarest and most valuable turquoise is found in the American Southwest— but the future of the blue beauty is unclear.

On a recent trip to Tucson, we spoke with fourth generation turquoise traders who explained that less than five percent of turquoise mined worldwide can be set into jewelry and only about twenty mines in the Southwest supply gem-quality turquoise. Once a thriving industry, many Southwest mines have run dry and are now closed.

C.

We found a limited supply of turquoise from Arizona and purchased it for our ***Sedona Turquoise Collection***. Inspired by the work of those ancient craftsmen and designed to showcase the exceptional blue stone, each stabilized vibrant cabochon features a unique, one-of-a-kind matrix surrounded in Bali metalwork. You could drop over $1,200 on a turquoise pendant, or you could secure 26 carats of genuine Arizona turquoise for **just $99**.

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Volume 111 • Number 6 • November–December 2023

## Departments



## Scientists' Nightstand

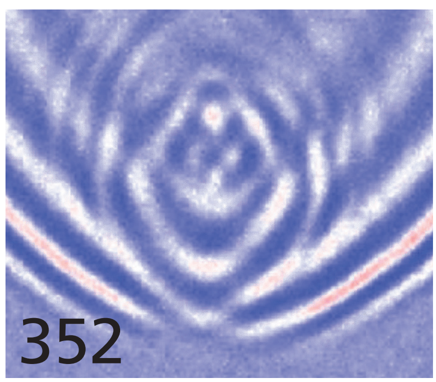


## From Sigma Xi



## Feature Articles







## The Cover

*Collagen is the body's most abundant protein, strengthening bone, teeth, tendons, skin, and the support sheets of the internal organs. Its ropelike structure comes from winding three stands of amino acids into a triple helix. The amino acids are linked together with amide bonds that include carbonyl groups (carbon–oxygen double bonds), and the strands wind into helices because of charge interactions between different amides along the chain. The positively charged regions around the carbon atoms in carbonyls are called π-holes, and they've sparked spirited discussions among chemists about their origins. In "(Don't) Shut Your π-hole" (pages 340–344), Dean J. Tantillo argues that the debates are productive if they help chemists design experiments to build better drugs, materials, and more. (Illustration by David Goodsell.)*

## From the Editors

# Talk It Out

Each discipline of science has its own debates in which evidence for one side or the other may not be particularly clear, because evidence can often be interpreted from different perspectives to support diverging conclusions. Sometimes there is more than one answer and both sides are right. And sometimes neither side is correct; the answer may lie at a point in between—or somewhere else entirely. The best approach that scientists can take is to give space to all theories that have sufficient evidence to merit serious consideration, and to expect that future work will continue to build the cases for and against those theories. At times, the debate itself can lead to advances.

In this issue's Perspective column, "(Don't) Shut Your π-Hole" (pages 340–344), Dean J. Tantillo informs us about one such debate within the world of chemistry. Molecules that have a neutral charge overall are nonetheless made up of elements and electrical bonds that create regions with more or less positive charge. Areas that are lacking electrons are termed either π-holes or σ-holes, depending on their shapes. But what causes "passion-filled debates," as Tantillo says, is defining what areas of the molecule really constitute a π-hole or a σ-hole, and determining how much these areas really mediate interactions between molecules. Tantillo believes that these debates are not only acceptable, but also fruitful, because they lead researchers to create new predictions that are then testable and can lead to new experiments, which in turn can have important practical outcomes, such as the development of a new cancer drug.

Research into communication itself was behind the imaging development that David M. Pepper and Todd W. Murray discuss in their article "'Seeing' into Opaque Materials with Light and Sound" (pages 352–359). Pepper and Murray discuss an early invention of Alexander Graham Bell, the *photophone*, which used sunlight to transmit voices. Bell observed what later came to be known as the *photoacoustic effect*, the formation of sound waves by the rapid thermal expansion and contraction of the air over a periodically heated surface. This effect underlies a current technique, *laser-based ultrasound*, which uses lasers to generate ultrasonic waves within opaque materials, the echoes of which are detectable at the material's surface and can be used to create images of what's inside.

In "How Herman Hollerith Counted America and the World" (pages 346–351), Ainissa Ramirez recounts how a chance conversation played an important role in events that contributed to modern computing. At a cocktail party, Hollerith, an inventor with an interest in tabulating machines, connected with a prominent member of the U.S. Census Office, and they ended up discussing the technology needed for counting the population. Eventually, after years of experimentation and a number of setbacks, Hollerith realized his dream of creating a tabulating machine that would modernize the processes of the Census. His system, which used punch cards, tabulated the results of the 1890 census, and drastically shortened the amount of time it took to come up with a rough count of the census, from seven years to six weeks. Hollerith's company later became part of IBM and the computer revolution.

The history of science is full of stories in which a random encounter or a new perspective kicked off a major innovation or resolved a longstanding enigma. Have you ever had a serendipitous experience or an unexpected result that changed the direction of your research? Join us on social media or write us a message through our website to tell us about it.
—*Fenella Saunders (@FenellaSaunders)*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VOLUME 111, NUMBER 6





***American Scientist*** gratefully acknowledges support for engineering content through the Leroy Record Fund.

# Readers Remember Henry Petroski

Courtesy of Catherine Petroski

To the Editors:
I was the editor-in-chief of *American Scientist* when Henry Petroski wrote his first Engineering column in the January–February 1991 issue. I had read and been impressed by his book *To Engineer Is Human* (St. Martin's Press, 1985). I really wanted to get more coverage of technology into the magazine, so I approached him about becoming a regular columnist. Henry was a little bit of a hard sell; he worried that having his work in the magazine would reduce sales of his books. But obviously he came around. Henry was such a reliable columnist—he always turned in clean copy on time.

One day in the 1990s, we met for lunch. He had just published yet another book. I was grumbling about the slow pace of progress on my own first book. Henry observed: "When I first thought about writing a book, it seemed intimidating. But then I sat down and did the math. If you just get up every morning and write a thousand words, books get finished quickly enough." Clearly, he was a man who took his own advice. I've always wished that I could have followed his example.

Brian Hayes
Chapel Hill, NC

To the Editors:
I was delighted to see Henry Petroski's final column in the July–August issue ("Building Knowledge"), and so sorry to learn he had passed on. He and I were classmates at Manhattan College. I saw him once at a reunion and we joked that at the time *American Scientist* had two columnists from Manhattan College. I miss him.

Peter Denning
Salinas, CA

To the Editors:
Thanks for your extensive and insightful essay about Henry Petroski. It is to his essay that I turned when I got a new edition of *American Scientist*. His prose was so clear and declarative. Henry's subjects were varied and always engaging. I and many readers will miss him.

Bob Chianese
Ventura, CA

To the Editors:
I am one of Sigma Xi's oldest members (since 1961, and I recently turned 91—and still working), and I've known Henry since 1985. He was hugely important in my professional life, right up there with my meeting with Albert Einstein.

On two occasions in the 1990s, I invited Henry to keynote a conference I was running—one on computer system trustworthiness and one on software engineering. In each case, his keynote made an enormous contribution to the entire conference. We had various ongoing communications, including discussions relating to his *American Scientist* columns. I submitted the following cover encomium for his last book, *Force* (Yale University Press, 2022):

> Henry Petroski is a true polymath with a superbly holistic perspective. This book is a unified field theory of almost everything, exploring the interdependencies among everyday forces and their effects. Albert Einstein would have loved it.

Peter G. Neumann
Palo Alto, CA

To the Editors:
Indeed, we shall all miss Henry Petroski and his Engineering columns very much! My favorite (not surprisingly) dealt with bridges made of unconventional materials, including frozen tomatoes ("Frozen Tomatoes and Other Construction Materials," May–June 2022). Henry was kind enough to credit me by name with the germ of that idea, which derives from the only joke my late Uncle Roy knew: Why is an old maid like a frozen tomato? Because it's hard ter-mate-er.

I had last emailed him a question about friction prompted by his column, "The Push and Pull of Friction" (November–December 2022). My question went unanswered, as did my final suggestion for a column on "Bridges in Song and Story"—the well-designed (*The Bridge on the River Kwai*) and poorly designed ("London Bridge Is Falling Down"); the judgmental (*The Bridge of San Luis Rey*) and the nonjudgmental ("Bridge over Troubled Water"). I suppose I shall have to write that one myself some day!

Virginia Trimble
Irvine, CA

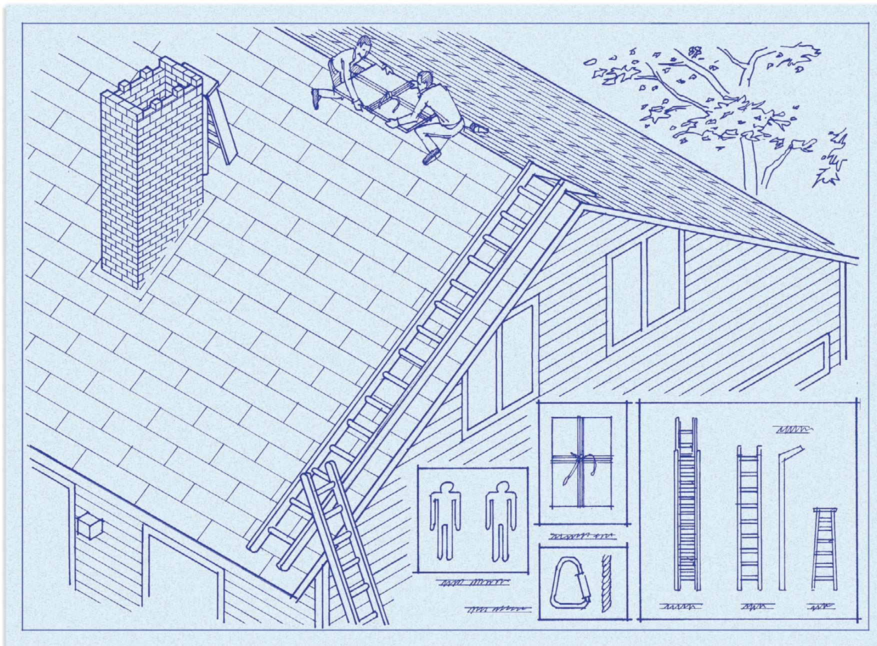
To the Editors:
I was so sorry to hear that Henry Petroski passed away. I always read and enjoyed his excellent articles on various engineering projects. I contacted him a number of times—most recently last year to share my experiences. He always responded to my emails. I will greatly miss him.

Joseph A. Castellano
San Jose, CA

To the Editors:
I am so sorry to read that Henry Petroski has passed. I was an avid reader of his *American Scientist* columns, as well as his books.

The two of us corresponded frequently on a wide range of subjects. We were like minds—curious and interested in virtually everything we saw around us. We had other things in common—we were both Manhattan College graduates, and we reminisced about our times there.

I am chemically- and mechanically-minded and he was soundly structural, but as soon as I heard about the Florida condo collapse (June 24, 2021), I thought of the salt air corrosion of rebar, and the expansion cracking of concrete on the columns. Henry bravely wrote a piece on the subject before studies were com-



Tom Dunne

**Henry Petroski's Engineering columns sometimes gave a peek into his personal life, such as the challenge of replacing the chimney cap on his house ("Occasional Design," January–February 2010). The breadth of his interests appealed to readers of all backgrounds, and those personal touches added warmth and developed a sense of kinship with his readers.**

pleted ("What Lessons Will Be Learned from the Florida Condo Collapse?" September–October 2021), and those factors were high on his list of likely causes.

He also wrote a more lighthearted piece on pesky light switches ("Solving Failures Around the House," January–February 2020). I wrote him a follow-up email to that article, sharing a clue to the issues he faced—switches that do not have "off" and "on" written on them are the three-way type. And so on as we wrote back and forth over the years.

Thomas F. McGowan
Atlanta, GA

To the Editors:
Like many readers of Henry Petroski's column, especially those of us professional engineers, I was deeply saddened to hear about his passing.

As an *American Scientist* subscriber and reader of his books, I have greatly enjoyed and learned a lot from Henry's insights. I wrote him an email once about my views on the philosophical aspects of practicing engineering. He wrote back within 24 hours with a very positive response. That was most appreciated as I'm sure he received many emails on engineering topics.

David Shteinman
Castlecrag, NSW, Australia

To the Editors:
I am a retired university professor and a physician. My undergraduate degree was in chemistry, not engineering. But I earned a PhD in engineering (industrial, not mechanical) at age 60 and taught it (as well as medicine) for 10 years prior to retiring. One of my combined passions in engineering and medicine was quality and safety, and that was my connection with Henry Petroski. I read all of his books and all of his columns in *American Scientist*.

Although I never met him, I always felt that we were "kin." I will look forward to future articles in *American Scientist*, but it will most certainly be different without him. I join the many who will deeply miss him.

Peter J. Fabri
Tampa, FL

To the Editors:
I was very sorry to learn of the passing of Henry Petroski. His column was my favorite in your magazine, and whenever I received a new issue I would quickly turn to Engineering and read it first. In 2017, I wrote a letter to the magazine in response to his article about the slide rule ("Slide Rules: Gone but Not Forgotten," May–June 2017), relating my own experiences with slide rules, electronic calculators, and pocket calculators.

As you mentioned in your In Memoriam article, he will be sorely missed, and you have made the right decision in retiring the Engineering column in his honor.

Henry C. Brenner
New York, NY

To the Editors:
Henry Petroski's columns were always the highlight of my reading in each issue of *American Scientist*. You are right to retire the Engineering column in his honor. His remarkable contributions will be sorely missed by many, including me.

Forman Williams
La Jolla, CA

To the Editors:
I was quite saddened to read today that Henry Petroski had passed away. His column was the one I immediately turned to when I received the latest issue of *American Scientist*. As a native of Brooklyn, his article on the Brooklyn Bridge was particularly exciting ("Altering an Icon," January–February). I'm very sad to see him go.

Paul Goldberg
Boston, MA

To the Editors:
Thank you for remembering Henry Petroski in the September–October issue of *American Scientist*. I always looked forward to Henry's columns, and I have read and enjoyed many of his books. I corresponded with him twice: once about his article on newspaper folding ("Industrial Origami," January–February 2005) and once concerning his article on the history and design of can openers ("Bottle and Can Openers as Levers," March–April 2017). In both instances, I received a personal and pertinent written reply.

Joe S. Herring
Rockport, TX

**How to Write to *American Scientist***

Brief letters commenting on articles appearing in the magazine are welcomed. The editors reserve the right to edit submissions. Please include an email address if possible. Address: Letters to the Editors, P.O. Box 13975, Research Triangle Park, NC 27709 or editors@amscionline.org

# Grow Young with HGH

From the landmark book Grow Young with HGH comes the most powerful, over-the-counter health supplement in the history of man. Human growth hormone was first discovered in 1920 and has long been thought by the medical community to be necessary only to stimulate the body to full adult size and therefore unnecessary past the age of 20. Recent studies, however, have overturned this notion completely, discovering instead that the natural decline of Human Growth Hormone (HGH), from ages 21 to 61 (the average age at which there is only a trace left in the body) and is the main reason why the the body ages and fails to regenerate itself to its 25 year-old biological age.

Like a picked flower cut from the source, we gradually wilt physically and mentally and become vulnerable to a host of degenerative diseases, that we simply weren't susceptible to in our early adult years.

Modern medical science now regards aging as a disease that is treatable and preventable and that "aging", the disease, is actually a compilation of various diseases and pathologies, from everything, like a rise in blood glucose and pressure to diabetes, skin wrinkling and so on. All of these aging symptoms can be stopped and rolled back by maintaining Growth Hormone levels in the blood at the same levels HGH existed in the blood when we were 25 years old.

There is a receptor site in almost every cell in the human body for HGH, so its regenerative and healing effects are very comprehensive.

Growth Hormone first synthesized in 1985 under the Reagan Orphan drug act, to treat dwarfism, was quickly recognized to stop aging in its tracks and reverse it to a remarkable degree. Since then, only the lucky and the rich have had access to it at the cost of $10,000 US per year.

The next big breakthrough was to come in 1997 when a group of doctors and scientists, developed an all-natural source product which would cause your own natural HGH to be released again and do all the remarkable things it did for you in your 20's. Now available to every adult for about the price of a coffee and donut a day.


GHR now available in America, just in time for the aging Baby Boomers and everyone else from age 30 to 90 who doesn't want to age rapidly but would rather stay young, beautiful and healthy all of the time.

The new HGH releasers are winning converts from the synthetic HGH users as well, since GHR is just as effective, is oral instead of self-injectable and is very affordable.

GHR is a natural releaser, has no known side effects, unlike the synthetic version and has no known drug interactions. Progressive doctors admit that this is the direction medicine is seeking to go, to get the body to heal itself instead of employing drugs. GHR is truly a revolutionary paradigm shift in medicine and, like any modern leap frog advance, many others will be left in the dust holding their limited, or useless drugs and remedies.

It is now thought that HGH is so comprehensive in its healing and regenerative powers that it is today, where the computer industry was twenty years ago, that it will displace so many prescription and non-prescription drugs and health remedies that it is staggering to think of.

The president of BIE Health Products stated in a recent interview, I've been waiting for these products since the 70's. We knew they would come, if only we could stay healthy and live long enough to see them! If you want to stay on top of your game, physically and mentally as you age, this product is a boon, especially for the highly skilled professionals who have made large investments in their education, and experience. Also with the failure of Congress to honor our seniors with pharmaceutical coverage policy, it's more important than ever to take pro-active steps to safeguard your health. Continued use of GHR will make a radical difference in your health, HGH is particularly helpful to the elderly who, given a choice, would rather stay independent in their own home, strong, healthy and alert enough to manage their own affairs, exercise and stay involved in their communities. Frank, age 85, walks two miles a day, plays golf, belongs to a dance club for seniors, had a girl friend again and doesn't need Viagara, passed his drivers test and is hardly ever home when we call - GHR delivers.

HGH is known to relieve symptoms of Asthma, Angina, Chronic Fatigue, Constipation, Lower back pain and Sciatica, Cataracts and Macular Degeneration, Menopause, Fibromyalgia, Regular and Diabetic Neuropathy, Hepatitis, helps Kidney Dialysis and Heart and Stroke recovery.

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### Connecting Memory and Imagination

Felipe De Brigard, a cognitive neuroscientist at Duke University, discusses the connection between *false memory*, which is the psychological experience of remembering something that did not happen, and *episodic counterfactual thinking*, which is imagining alternative ways that past personal events could have occurred.
*www.amsci.org/node/5131*

### Change Is the Only Constant

Kristin Poinar reviews Elizabeth Rush's book *The Quickening: Creation and Community at the Ends of the Earth*, which documents an Antarctic expedition to Thwaites Glacier alongside questions of what it means to decide to have a child in the face of climate change.
*www.amsci.org/node/5130*

### An Inside Look at COVID-19 Policies

If the Q&A with Linsey Marr in the September–October issue piqued your interest, check out the companion podcast for a deeper dive into the evolution of COVID-19 responses. The Virginia Tech engineer spoke with *American Scientist* digital features editor Katie L. Burke about how research into the airborne spread of SARS-CoV-2 helped shape U.S. and international policy during the epidemic.
*www.amsci.org/node/5124*

### Fall STEM Reads of 2023

Find new releases for your #ScienceSeptember book stack and beyond.
*www.amsci.org/node/5127*

### A Broader Look at Modeling

The AmSci editors curated a collection of past content related to the July–August special issue on scientific models.
*www.amsci.org/node/5105*

### Trailblazing Women Botanists in the Grand Canyon

Elzada Clover and Lois Jotter mapped the botany of the Grand Canyon, but their adventure down the Colorado River has largely gone unnoticed. Melissa L. Sevigny's book *Brave the Wild River* adds their contributions to the narrative.
*www.amsci.org/node/5129*

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# Engineering for Heat Waves

*Higher temperatures cause machines to overheat, batteries to lose power, and roads to buckle, crippling infrastructure systems.*

Humans weren't the only ones who needed to stay cool during 2023's record-breaking heat waves. Many machines, including cell phones, data centers, cars, and airplanes, become less efficient and degrade more quickly in extreme heat. Machines generate their own heat, too, which can make hot temperatures around them even hotter.

No machine is perfectly efficient—all machines face some internal friction during operation. This friction causes machines to dissipate some heat. That dispelled heat mixes with the external temperature, so the hotter it is outside, the hotter the machine will be.

Cell phones and similar devices with lithium-ion batteries experience decreased performance when operating in climates above 35 degrees Celsius (95 degrees Fahrenheit). This throttling is by design to avoid overheating and increased stress on the electronics.

Designs that use innovative phase-changing fluids can help keep machines cool, but in most cases heat is still dissipated into the air. So, the hotter the air, the harder it is to keep a machine cool enough to function efficiently. Plus, the closer together machines are, the more dissipated heat there will be in the surrounding area.

We are engineering researchers who study how machines manage heat, as well as ways to effectively recover and reuse heat that is otherwise wasted. Technologies for reducing, capturing, and reusing heat could help prevent mechanical failures and weakened infrastructure systems during an era of rising temperatures.

### Deforming Materials

Higher temperatures, either from the weather or from the excess heat radiated from machinery, can cause materials in machinery to deform. To understand why, consider what temperature means at the molecular level.

At the molecular scale, temperature is a measure of how much molecules are vibrating. The hotter the temperature, the more the molecules that make up everything from the air to the ground to materials in machinery vibrate.

As the temperature increases and the molecules vibrate more, the average space between them grows, causing most materials to expand. Roads are one place to see this happen—hot concrete expands, gets constricted, and eventually cracks. This phenomenon can happen to machinery, too, and thermal stresses are just the beginning of the problem.

**Waste heat from power plants could support 27 percent of residential air-conditioning needs.**

### Travel Delays and Safety Risks

High temperatures can also change the way oil in your car's engine behaves, leading to potential engine failures. For example, if a heat wave makes it 16.7 degrees Celsius hotter than normal, the viscosity of typical car engine oil can change by a factor of three.

Fluids such as engine oils become thinner as they heat up, so if it gets too hot, the oil may not be thick enough to properly lubricate and protect engine parts from increased wear and tear.

Additionally, a hot day will cause the air inside your tires to expand and raise the tire pressure, which could increase wear and the risk of skidding.

Airplanes are also not designed to take off at extreme temperatures. As it gets hotter outside, air expands, making it thinner or less dense. This reduction in air density decreases the amount of weight the plane can support during flight, which can cause significant travel delays or flight cancellations.

### Battery Degradation

In general, the electronics contained in devices such as cell phones, personal computers, and data centers consist of many kinds of materials that all respond differently to temperature changes. These materials are all located next to one another in tight spaces. So as the temperature increases, the types of materials deform differently, potentially leading to premature wear and failure.

Lithium-ion batteries in cars and electronic devices degrade faster at higher operating temperatures. Heat increases the rate of reactions within the battery, including corrosion reactions that deplete the lithium levels, which in turn reduces the battery's storage capacity. Tests conducted by Recurrent (a company that provides car and battery information for the secondary electric vehicle market) found that electric vehicles can lose about 20 percent of their range when exposed to sustained 32-degree-Celsius (90-degree-Fahrenheit) weather.

Data centers full of computer servers dissipate significant amounts of heat to keep their components cool. On very hot days, fans must work harder to ensure chips do not overheat, and in some cases, powerful fans are not enough to cool the electronics.

When the data centers need a stronger cooling system, they often turn to *evaporative cooling*. This method sends incoming dry air from the outside through a moist pad. The water from the pad evaporates into the air and absorbs heat, which cools the air. This technique is usually an effective and economical way to keep chips at a reasonable operating temperature. However, evaporative cooling can require a significant amount of water, which is problematic in regions where water is scarce. Water for cooling can add to the already intense resource footprint associated with data centers.

Air conditioners struggle to perform effectively as it gets hotter outside—just when they're needed the most. On hot days, air conditioner compressors have to work harder to send the heat from homes outside, which in turn disproportionately increases electricity

Paul Smyth/Alamy Stock Photo

**A heat wave in July 2022 caused major cracks in a roadway in Kingston upon Thames, a town in Greater London. Concrete expands in high heat, as do many other materials crucial to infrastructure and technology. Engineers and materials scientists are studying ways to manage increasing temperatures, including how to capture and reuse expended heat from machines and other devices.**

consumption and overall electricity demand. For example, in Texas, every increase of 1 degree Celsius creates a rise of about 4 percent in electricity demand.

Heat leads to a staggering 50 percent increase in electricity demand during the summer in hotter countries, posing serious threats of electricity shortages or blackouts, as well as higher greenhouse gas emissions.

### Reusing Heat

Heat waves and warming temperatures around the globe pose significant short- and long-term problems for people and machines alike. Fortunately, there are ways to minimize the damage.

One is to ensure that machines are kept in air-conditioned, well-insulated spaces out of direct sunlight. Another is for consumers to use high-energy devices, such air conditioners and electric vehicle charging stations, during off-peak hours when fewer people are using electricity.

Individual changes at the consumer level will not solve the problem alone, so scientists and engineers are developing ways to use and recycle the vast amounts of heat dissipated from machines. One simple example is using the waste heat from data centers to heat water. Waste heat could also drive other kinds of air-conditioning systems such as absorption chillers, which use heat as energy to support coolers through a series of chemical- and heat-transferring processes.

In both of these examples, the energy needed to heat or cool something comes from heat that is otherwise wasted. Indeed, one of us (Garimella) collaborated on a 2011 study that found that waste heat from power plants could support 27 percent of residential air-conditioning needs, which would result in a dramatic reduction of overall energy consumption and carbon emissions.

Extreme heat can affect every aspect of modern life, and heat waves aren't going away in the coming years. However, there are opportunities to harness extreme heat and make it work for us.

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# INTERNATIONAL FORUM ON RESEARCH EXCELLENCE

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Adriana Banktson

STEM Academic Research and Training (START) Ambassadorship: Empowering future researchers through common grounds
Kevin Reza-Villa

Excellence in networking: Showcase yourself and your work with confidence
Allison Coffin

Vital Communication Skills
Brian Palermo

How to Create Artificial General Intelligence (AGI) and Not Die
Craig Kaplan

Utilizing the Anatomage Digital Technology to Address Challenging Concepts in Health Science Education
Rima Khankan

Considerations of AI in Healthcare: Clinical, Coordination, Management, and Research Perspectives
Zihan (Ellis) Gao

Teaching Ethics in AI: A Practical Workshop for Educators
Richard Whittington

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# DANDELIONS: DIURETICS AND RUBBER

## DANDELIONS' MEDICINAL USES

The French name for dandelion is *pissenlit* ("wet the bed"), which refers to the plant's use in traditional medicine as a diuretic. Dandelions do contain several diuretic compounds, and limited studies in humans have confirmed their therapeutic efficacy. The plant's high potassium content also helps replace potassium lost through urination.

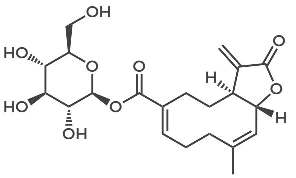
**potassium content of dandelion leaves versus bananas**

**dandelion leaves**
**397 milligrams per 100 grams**

**bananas**
**358 milligrams per 100 grams**

*Source: U.S. Department of Agriculture FoodData Central*

Dandelion extracts and compounds have anti-inflammatory, anticarcinogenic, and antioxidative properties. These effects are mostly due to *polyphenols* and *sesquiterpenes*, phytochemicals that are also responsible for the leaves' bitter flavor.




**taraxinic acid β-D-glucopyranoside**

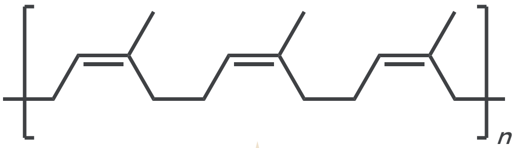
*sesquiterpene lactone in dandelions, also thought to be a contact allergen*

## RUBBER FROM DANDELIONS

The sticky white liquid that seeps from dandelion stems when they're picked contains natural latex, which can be turned into rubber. The roots of Russian dandelions (*Taraxacum kok-saghyz*) contain a particularly high percentage of latex, making them ideal for rubber production.

**1941 30%**

**During World War II, nearly one-third of the USSR's rubber was derived from the Russian dandelion to compensate for a shortage of natural rubber.**




**cis-1,4-polyisoprene (main constituent of rubber)**

In the past decade, tire manufacturers have developed dandelion-rubber tires. Bike tires made from this rubber are now commercially available, and manufacturers estimate that dandelion-rubber tires will be available for cars and trucks within the next 10 years.

# Poverty and Neuroscience

*In the past few years, there have been major initiatives to increase diversity, equity, and inclusion (DEI) in science and in the workforce. Yet the root causes of inequities are still being revealed. Neuroscience researchers are suggesting that poverty is a major player—noting that poverty is contributing to decreases in academic success, education level completed, and even brain mass. Gabriel Reyes, a PhD student in developmental and psychological sciences at Stanford University, is working at the heart of this subject. Reyes grew up in a low-income, underserved section of Albuquerque, New Mexico, where opportunities were limited. Nevertheless, his passion for neuroscience led him to attend Brown University, Columbia University, and now Stanford. He is the first in his family to graduate from college and is working at the intersection of DEI and neuroscience research. Reyes is also the founder of FLi Sci, a program that provides research opportunities to first-generation and low-income science students. Reyes attended Sigma Xi's 2022 International Forum on Research Ethics (IFoRE), which focused on science convergence in an inclusive and diverse world, and spoke with Jordan Anderson, producer of* American Scientist*'s* DEAIComSci *podcast, about debunking poverty and educational inequity myths, and what current neuroscience research reveals about a path toward more equitable educational outcomes for students nationwide. (This interview has been edited for length and clarity.)*


Courtesy of Gabriel Reyes

**What pressing issues in neuroscience does your research explore?**

My research has two buckets. The first bucket is neuroscience and understanding how experiences and the environment affect our behavior. I had planned to understand how specific experiences influence decision-making. Two scientists who inspired me were Kim Noble and Bruce McCandliss, who are examining whether there is a correlation between poverty and academic achievement from a neuroscientific standpoint. Dr. Noble, at Columbia University, has written a lot of papers on poverty and brain development. Dr. McCandliss teaches at Stanford University and runs the Educational Neuroscience Initiative, using neuroscience to improve learning. Their work created a path for me to explore the associations between socioeconomic status and brain development and to theorize how that might translate into academic performance. But I didn't get anywhere with that topic, because I was finding more research questions than insights.

As I was learning more about the field, I began to realize that there are two problems. One is that how neuroscientists theorize and conceptualize poverty needs to be more consistent. For some people, poverty is defined by how much income your family makes. For another person, poverty might be defined by specific experiences communities endure. Are they able to pay rent on time? Are they in a lot of debt? Are they experiencing a lot of stress? This discrepancy is a conflict, because both definitions are related but are different constructs and therefore have different conclusions.

The second issue was that we still need to fully understand fundamental learning mechanisms. How can we speak to how people from low-income versus high-income backgrounds learn, when we're still figuring out how people generally learn? We are exploring how to bridge the two without problematizing the work. We want to avoid jumping to conclusions that have yet to be reached in neuroscience.

> **"We are looking at large datasets with a myriad of income analyses and thinking through how the story changes if you alter how you define poverty."**

I want to start first by thinking about poverty as a construct. At Stanford, many of my projects interrogate how the field has measured poverty and whether we're measuring it correctly. The most common index that I see these days is an income-to-needs ratio. And that is a federal poverty index, where officials define poverty by household income. However, for example, many neuroscience studies need to consider that in New York City and the San Francisco Bay Area, rent is much higher on average than in rural Alabama. In rural places, $30,000 can take you much farther, but won't get you very far in vast urban areas. That's a massive issue for data analysis. Part of what I am now working on with Philip Fisher at Stanford is looking at large datasets with a myriad of income analyses and thinking through how the story changes if you alter how you define poverty. We want to explore the general theory of poverty in a way that speaks more to the environments that people experience. So that's the second bucket of my research.

**You were exploring how poverty affects cognitive development with Dr. Noble. Can you give an example of how you are applying your previous neuroscience work to your current PhD research with Dr. Fisher, and how you are examining the definition of poverty?**

Researchers such as Dr. Noble have found a particular association between looking at one's socioeconomic status and the amount of cortical volume in particular individuals. Often, what they see is that there is a positive association between cortical volume and income. However, it is a nuanced ques-

tion, because cortical loss in higher-income communities does not mean equal or more significant cortical loss in people with lower socioeconomic status. Some studies don't find that association. There are a lot of other variables, such as the research participant's school and how socioeconomic status is measured.

Researchers in this field are pushing toward different ways of understanding brain development, looking at nuanced ways of thinking through socioeconomic status. One of the ways is looking at experience with material deprivation or other factors beyond just the income-to-needs ratio to understand what happens with brain development. People who experience certain forms of economic adversities, such as food insecurity, are often more likely to have differences in cognitive function, cognitive behavior, and neural development. Some people don't experience food insecurity but might be in the same income bracket.

**What sort of data are you exploring in your current research, and how is it affecting the field of neuroscience?**

In my research, I analyzed data from the Fragile Families and Child Wellbeing Study. I was looking at various outcomes, one of which is working memory. That is an aspect of executive function—mental processes that enable us to plan, focus attention, remember, and juggle multiple tasks. It measures how much information people can hold at any given moment and is a typical topic in cognitive studies. It is also one where people often find things such as the association that people with lower income generally have lower working memory capacity than someone with higher income. And I used a friend's framework for how we think about that to look at it through a different lens. So instead of just looking at the effect of income on performance, I wanted to see how people who experience more aspects of material deprivation behave throughout different income barriers.

For example, someone who makes $10,000 and someone who makes $90,000 represent people in two separate income groups. But let's say the person who earns $90,000 lives in a costly part of San Francisco and supports a family of eight. $90,000 may seem like a lot, but it doesn't go that far when you think about how they're using that money versus someone who is making $10,000 but is a single adult living somewhere like New Mexico. You can then ask questions like: Can you pay your rent on time? Did you make enough money to pay the electricity bill? Are you able to go to the hospital? Or did you not go to the hospital because you couldn't afford the medical bill? We add up the number of those experiences and see that maybe someone who's making $10,000 only had two moments of material deprivation for the questions we asked, but the person making $90,000 had nine of those moments out of 10. We want to see if there was an association between that sort of interaction effect with income and experiences of scarcity. My initial research found that income as a single variable is insufficient to understand how poverty affects cognitive development. Higher levels of material deprivation can affect performance and working memory tasks for people across different income groups. We would not have found that association if it was just income alone.

> **"Instead of just looking at the effect of income on performance, I wanted to see how people who experience more aspects of material deprivation behave throughout different income barriers."**

One of the things that we want to do is to see if we can measure qualitative rather than quantitative responses by creating written response questions on a massive survey database. By doing so, we can extract specific factors of the poverty experience that we can use to uncover a different way of categorizing family and community poverty without looking at income.

**How has the research in your field changed over time?**

Many studies have divided tasks or groups of people by low income, high income, or middle income. It could be a quick correlation task that measures a behavioral outcome such as test scores. Based on prior studies, we might theorize that low-income people will have lower test scores than higher-income people. The problem is that this does not provide the root cause of what is happening. It also implies that low-income people are less capable than high-income people at standardized testing. This logic is not accurate. Even if those associations are occurring, income is not causing test performance. Instead, income might produce specific experiences in which higher-income people can score higher.

Rather than asking people what their income is and dividing them by those groups, we can add a second variable that asks questions such as: Did you get access to private tutoring on the SAT or ACT? Did you attend a rigorous high school that provided resources to learn how to perform well on standardized testing? Now we have questions that might get to experiences contributing to test performance. If you add this dimension on top of income, we might find that, for example, low-income students who scored highly on the test had access to private tutoring or went to top-tier high schools. We may also find that low-income students who performed poorly had none of these resources. This pattern also exists in middle-income groups and high-income groups.

Neuroscience researchers are currently working on these insights, and we are building off of them. Applying that to the brain, we can see that there might be differences in cognitive performance and neural signatures when you only look at income, but we have started adding all these other measurements, such as: Are you experiencing high levels of threat? Are you experiencing high levels of food insecurity? Are you experiencing high levels of monetary scarcity? These new insights have created a differentiation between our knowledge of which part of the brain has specific patterns, which tells us that it's not just income but rather experiences that income is either allowing or preventing some groups to have more often than others that are contributing to brain mass.

**How have your personal experiences influenced your choice of research?**

I often had to turn down research opportunities that I knew would help me be a better scientist. I was poor, and I could not afford the opportunities. I would be

pushed away if I tried to advocate for financial assistance. In my undergraduate years, I had the chance to work on my thesis with a researcher I love, but I needed a lot of money to help my parents hire an immigration attorney. So instead, I worked for Google because they offered a larger salary. Two months as a full-time research assistant would barely pay rent. In my master's program, a similar situation occurred where I could not afford to take the research assistant salary. So, I needed to figure out how to find a way to continue training as a researcher while managing my family's financial circumstances. And the thing that galvanized me to create a program during my PhD that would allow me to support other students born into low-income situations like myself was knowing that I could more easily have become a scientist if I only had had a little more financial support.

**Much of your neuroscience research is geared toward DEI. Are there other DEI spaces that you are involved in?**

For many people who try to do scientific research, it is often hard to avoid diversity, equity, and inclusion efforts, because we often have to point out scientific injustices or champion for spaces for us to exist. So, on the one hand, I focused on poverty and development in psychology. On the other hand, I also do a lot of work in science education and diversity in science. One of the projects I am involved in is figuring out the antecedent to academic career success. We want to find the common factors that help people transition from an undergraduate experience to a tenure-track profession, especially for minoritized scientists.

**"We want to find the common factors that help people transition from an undergraduate experience to a tenure-track profession."**

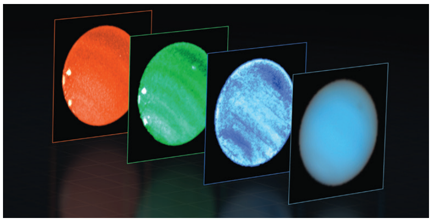
Another major project I am involved in is called FLi Sci. In the summer of 2020, every scientist talked about diversity and inclusion in science. Implementing graduate mentorship programs was their number-one solution to provide more diversity efforts. Although these programs are important, scientists often pose them as the only solution. The root cause starts a lot sooner than college programs. I wanted to target high school students who went to lower-income schools, like I had, to prepare them earlier for college and graduate school. The goal was not to let lower-income students become college seniors lacking the research experience they needed to be competitive for PhD programs.

Many students do not have enough experience to get postbaccalaureate opportunities, because it's so competitive nowadays for people to get opportunities without a research background. So, I created FLi Sci because I was looking for other nonprofits targeting low-income or non–high-achieving high school students. Often, these programs accepted previously accomplished students. They were students who did well on the PSAT or went to a magnet school. I struggled to find a program trying to recruit students without those opportunities. So, I decided to create it and see what would happen. ■

In this roundup, managing editor Stacey Lutkoski summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi/index.jsp

## Neptune's Cloudy Weather

For the first time, Earth-bound astronomers have peeked beneath the surface atmosphere of the Solar System's most-distant planet to understand the roots of its extreme and surprisingly dynamic weather. A team led by physicist Patrick G. J. Irwin of the University of Oxford used the European Southern Observatory's Very Large Telescope (VLT) to capture images of a 10,000-kilometer-wide dark spot on Neptune's northern hemisphere. They paired the VLT with a tool called the Multi-Unit Spectroscopic Explorer, or MUSE, which takes images at multiple wavelengths. Each wavelength probes at a different depth, and together they



ESO/P. Irwin et al.

create a composite 3D image. MUSE revealed that the dark spot is composed of icy, hazy air particles in a layer beneath the outer atmosphere. This finding rules out a previous theory that the dark spot is caused by clearing clouds. MUSE also uncovered something unexpected: a bright spot next to the dark spot. The bright spot is at the same depth as the dark spot but had not previously been identified, even by space-based telescopes, and appears to be a new type of cloud. The team's discoveries using MUSE show new ways to use remote sensing from Earth to study the intense and complex weather systems on distant planets.

*Irwin, P. G. J., et al. Spectral determination of the colour and vertical structure of dark spots in Neptune's atmosphere.* Nature Astronomy *doi:10.1038/s41550-023-02047-0 (August 24).*

## Mental Toll of School Closures

Parents' and educators' anecdotal evidence of the psychological toll of school closures on children during the COVID-19 pandemic now has the backing of data. Researchers led by economist Christina Felfe of the University of Konstanz in Germany used the German school system as a natural experiment to study the effects of school closures on children aged 11 to 17. They found that longer school closures correlated with worsening mental health measures, especially among boys, younger adolescents, and those living in close quarters. Each of the 16 German federal states manages their public schools independently, so although all of the states closed their schools between March 16 and March 18 of 2020, the reopening dates ranged from April 20 to June 15 of that year, and return-to-school strategies varied. The researchers merged information on school closures with mental health data collected by German national health surveys of 11- to 17-year-olds. They first compared responses from students at different grade levels in the same state to isolate any state-specific variables and then looked at students at the same grade level in different states to assess age-specific variations. The team found that each additional week of school closure was associated with a decrease in measures of the students' health-related quality of life, and longer closures correlated to prolonged mental health disorders. These findings support the need for ongoing mental health services for school-age children and may help shape education policies in the case of a future pandemic.

*Felfe, C., et al. The youth mental health crisis: Quasi-experimental evidence on the role of school closures.* Science Advances *9:eadh4030 (August 18).*

## Fire Ants Cross the Atlantic

The invasive species *Solenopsis invicta*, commonly known as the red imported fire ant, has established a colony in Sicily, marking the first mature population in Europe. These insects threaten the local agriculture and ecosystems—a 2021 study in *Nature* ranked them as the fifth most costly invasive species—and their painful bites can cause severe allergic reactions in some people. A team of Spanish and Italian biologists documented 88 nests over 4.7 hectares in eastern Sicily. The species has reached Europe at least three other times but was intercepted before it could spread; however, the size and range of the Sicilian colonies mean that eradication is not likely to succeed. Approximately 7 percent of Europe currently has environmental conditions in which the ants would thrive; however, global climate change could extend the habitable area to 25 percent of the continent by 2050. Red imported fire ants are native to South America but have spread to Mexico, the United States, the Caribbean, Australia, and parts of Asia. They hitch rides on boats and plants and are also dispersed by the wind, which can carry queens on their flights to establish new colonies.

*Menchetti, M., et al. The invasive ant* Solenopsis invicta *is established in Europe.* Current Biology *33:R879–R897 (September 11).*

## Uncovering Pompeii's Slaves

An addendum to the saying "History is written by the winners" might be "and by the elite," because those groups have historically had the education to record their affairs and the money to buy objects that survive as artifacts. So the 2021 discovery of Roman slave quarters in the villa of Civita Giuliana outside Pompeii was a coup for historians, and new findings from the excavation add nuance to our understanding of slavery in the Roman Empire. Two rooms, preserved in ash from Mount Vesuvius's eruption in 79 CE, provide a glimpse into the lives of their enslaved inhabitants. One room had three beds, one of which was short, perhaps for a child. The inhabitants slept on ropes tied into loose netting, similar to the design of many modern hammocks. The other room had a similar rope bed and also another, more comfortable bed that would have had a mattress. The archaeologists theorize that this bed may have belonged to a higher-status servant. Neither of the bedrooms nor the nearby stable had bars on the windows or locks on the doors to keep the slaves imprisoned, which suggests that the villa's owners used other methods of control—the researchers suggest that the close quarters and the presence of the higher-status servant may have encouraged the slaves to police each other. Slavery was an important aspect of Roman society, but most accounts come from the perspective of the ruling class. These bedrooms inform historians' understanding of how Roman slaves lived and the mechanisms for control slaveowners employed.

*Zuchtriegel, G., and C. A. Corbino. Of mice and men: New discoveries in the servants' quarters of the Roman villa of Civita Giuliana near Pompeii.* Scavi di Pompei *5 (August 20).*

# Uncovering Ancient Corrections

*Pigment fluorescence reveals artistic revisions beneath Egyptian tomb murals.*

The intricate and extensive murals that adorn the walls of ancient Egyptian tombs are no doubt masterful works of art, but their method of creation has long been thought of as having been a regimented production line rather than a free-flowing artistic process. Various levels of artisans were relegated to adding only their assigned layers to each of the illustrations, leaving little room for rethinking the approach. The style used to depict the poses, colors, and decorative elements of deities or others was also highly formalized, not left to the imagination of any particular artist. However, advances in imaging technology have now uncovered corrections and revisions to the tomb figures, bringing into question the accepted view of the process of these Egyptian artists millennia ago.

Archaeologist Philippe Martinez of Sorbonne University in France and a large team of his colleagues describe how they revealed these alterations in the July 12 issue of the journal *PLOS ONE*. The researchers were examining the tomb chapels of high-ranking officials near the ancient city of Thebes (now Luxor) from what's called the New Kingdom, which lasted from about 1549 to 1069 BCE, encompassing the 18th to 20th dynasties. "The walls of these shrines were often decorated, representing the dead in his dutiful life on Earth as well as his expectations for a bright future in the netherworld," Martinez and his colleagues explain in their paper.

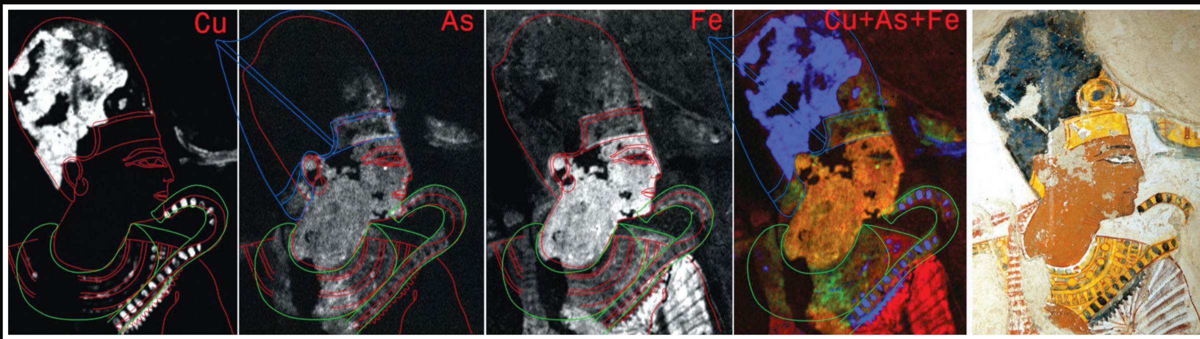
Previously, the pigments used in these tomb scenes had been analyzed mostly by taking tiny samples back to laboratories. But the team of researchers had created a portable version of an imaging device that uses x-ray fluorescence to look at pigments, without contact or damage, while still in place in the tombs. The pigments used by ancient Egyptian artists are suitable for this type of imaging, because the different elements fluoresce at distinct wavelengths when they are bombarded with x-rays, and the rays can penetrate the top surface of paint to reveal other elements underneath. This portable x-ray fluorescence (pXRF) device is small enough to be checked luggage on an airplane, the team notes.

The researchers became interested in focusing their work on artistic corrections when they were examining a known revision that had become slightly visible through the millennia-old wear and chemical reaction of paint, in the tomb chapel of Menna, an overseer under Amenhotep III, 1391–1353 BCE. The revision was made to the position of Menna's arm, shown in a ritualized pose of adoring Osiris (*see figures on opposite page*). One surprise the team found was that the pigments used in the original and the corrected arms have different compositions, with the first version high in arsenic (common in realgar, a red pigment) and the revised version containing more iron (common in red ochre). That difference could mean that the correction was made by another artist at the same time using a separate batch of pigment, or that the change happened later. The purpose of the rather small position adjustment remains unclear, however.

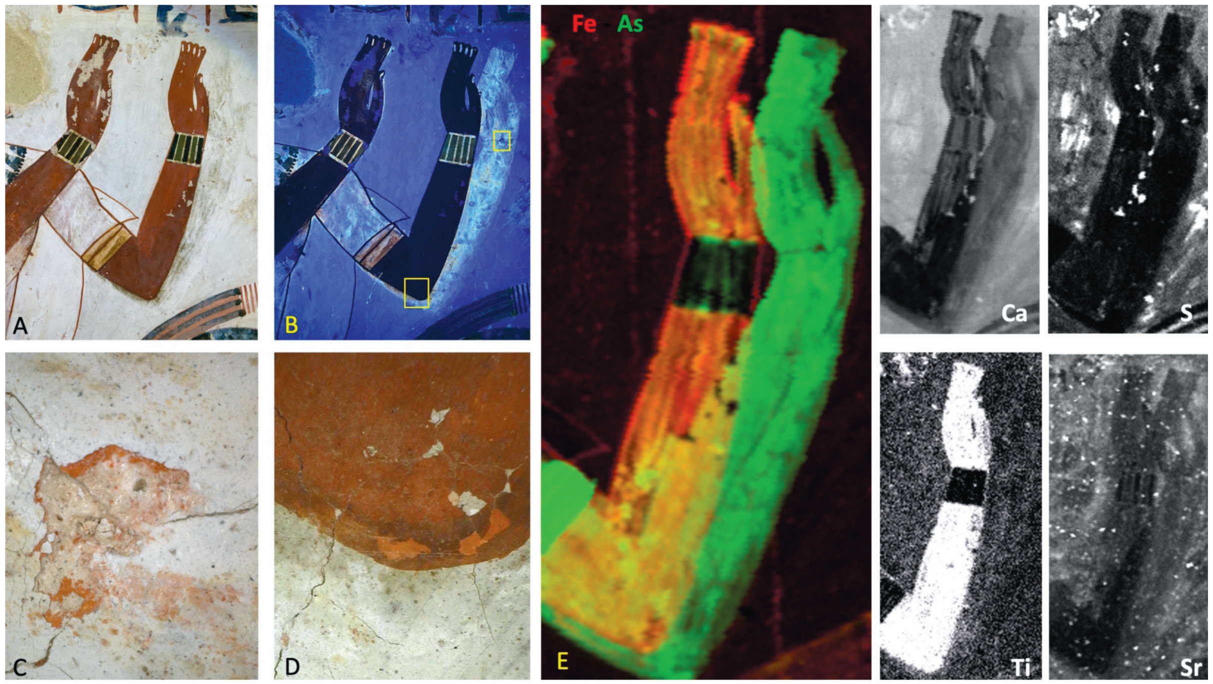
The second tomb chapel the team examined belonged to Nakhtamun, chief of the altar in the Ramesseum temple, in about 1100 BCE. Because this tomb features a portrait of Ramesses II, it has usually been dated to his reign. However, some inconsistencies with standard Egyptian iconography, including beard stubble and an Adam's apple, inspired Martinez and his team to take a closer look. Their pXRF showed signatures of copper, characteristic of the pigments Egyptian blue and green, even though these colors are barely visible now. Another hidden detail they revealed was that the original scepter (called a *heka*) appears to have been wider and to have obscured part of the chin. Indeed, the portrait seems to have had all its pharaonic insignia retouched: The crown (or *khepresh*) and necklace (or *wesekh*) originally had quite different shapes. Martinez and his colleagues note that the original depiction more closely resembles a necklace style called a *shebyu*, which was common in royal portraits from the 20th dynasty, after the death of Ramesses II. The team speculates that this change could indicate that the tomb dates later than originally thought, after Ramesses II had become deified, and that the original depiction had been recognized to be anachronistic and was thus repainted. "A lot of this modern and theoretical reconstruction is, however, based on the usual archaeological guessing game that aims at filling the remaining blanks," Martinez and the team say. "We remain clearly ignorant of what was really important and significant for the ancient Egyptian eye and mind."

As was the case with the team's imaging of the trace remnants of Egyptian blue and green, this pXRF method could also have the potential to help with reconstructing areas of these ancient tombs that have been damaged or weathered to the point that their murals are no longer visible, but which might retain pigment residues that could still be detectable. The researchers also hope to undertake a more systematic inspection of other tomb murals to try to characterize how common corrections were. "Due to the fact that most of the scientific inspections of these works of art have been carried out only through direct visual observation," they say, "this may very well be but the tip of the iceberg." —*Fenella Saunders*

Top and bottom from P. Martinez et al., *PLOS ONE* 18(7):e0287647. Middle: M. Alfeld et al., *Comptes Redus Physique* 19:625.




**A portable x-ray fluorescence (pXRF) device set up in an ancient Egyptian tomb chapel (*right*) is able to reveal pigments beneath a mural's surface layer, because different pigments fluoresce at distinct wavelengths when bombarded with x-rays. In this mural, the arm of the official Menna was altered from its original pose. The correction is slightly visible now (*A, below*) because of paint wear and chemical reactions over millennia. The change shows up more clearly under ultraviolet light (*B*). Details of the correction (*C and D*) show pigment interactions. The original arm pigment contained more arsenic (As, *in E*), and the correction was higher in iron (Fe); the two also show differences in calcium (Ca), sulfur (S), titanium (Ti), and strontium (Sr). In another tomb (*above*), a depiction of Ramesses II shows changes in the shape of the necklace, crown, and staff, as is made visible by pXRF imaging of copper (Cu), arsenic, and iron (*green lines show earlier version, red lines show correction, and blue lines show original shape of this style of crown, called a* khepresh).**



# (Don’t) Shut Your π-Hole

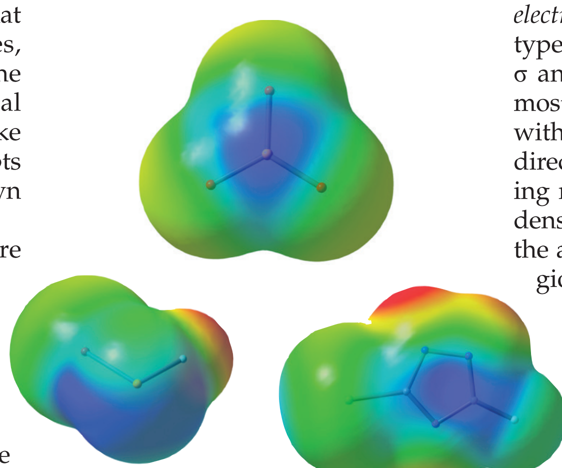
*Like charges repel and opposite charges attract. That law of physics dominates organic chemistry and our everyday lives—and causes feuds among chemists.*

Dean J. Tantillo

Attractions and repulsions form the basis of chemistry, including the biochemistry that allows our cells to function and the organic chemistry that enables much of the modern chemical industry. If you want to know how a new drug will interact with a disease-causing protein, or if you want to investigate the ways that cells build their internal structures, you ultimately need to examine the pushes and pulls between electrical charges. That sounds simple, but like everything in nature, simple concepts turn really hairy when you dig down into the details.

Even though most molecules are not charged overall, they have regions that are more negatively or positively charged—places that naturally want to balance their situation by interacting with an oppositely charged part of another molecule. That hunger for balance is the basis of most chemical interactions, leading molecules to point their electron-rich parts at the electron-deficient parts of other molecules. For example, organic chemists commonly talk about an electron-rich group, or *nucleophile*, approaching an electron-poor carbon atom within a carbonyl (carbon double-bonded to oxygen) group and “attacking” it to form a new bond. Carbonyl groups are present in many important biomolecules such as sugars, lipids, and peptides, so such reactions are key to life. These reactions help amino acids assemble to form proteins, such as collagen, and allow cells to digest proteins when they are no longer needed.

Chemists have discussed carbonyl chemistry for approximately a century, but a relatively new term has arisen to describe the electron-deficient property of carbonyls and other similar bonds: the *π-hole*.



Dean Tantillo

**When covalent bonds form, electrons are shared, often unequally, across multiple atoms, resulting in regions of positive and negative charge even in molecules that are neutral overall. Chemists create electron density maps to visualize these patterns known as *σ-holes* and *π-holes*. In the example above, blue regions have greater negative charge, red areas have more positive charge, and green and yellow areas have intermediate charge. Selenium fluorobromide (*lower left*) has a σ-hole. Sulfur trioxide (*top*) and chlorofluorotetrazole (*bottom right*) both have π-holes.**

Organic molecules are held together by bonds that share electrons, but chemists don’t think of electrons simply as particles or points. Instead, they describe them as smears of charge between atoms, a concept known as *electron density*. There are two primary types of these electron-sharing bonds: σ and π (*sigma* and *pi*). In a σ-bond, most of the electron density associated with the bond is distributed around a direct line between the two neighboring nuclei. In π-bonding, the electron density resides either above or below the atoms but not in the sandwich region connecting them.

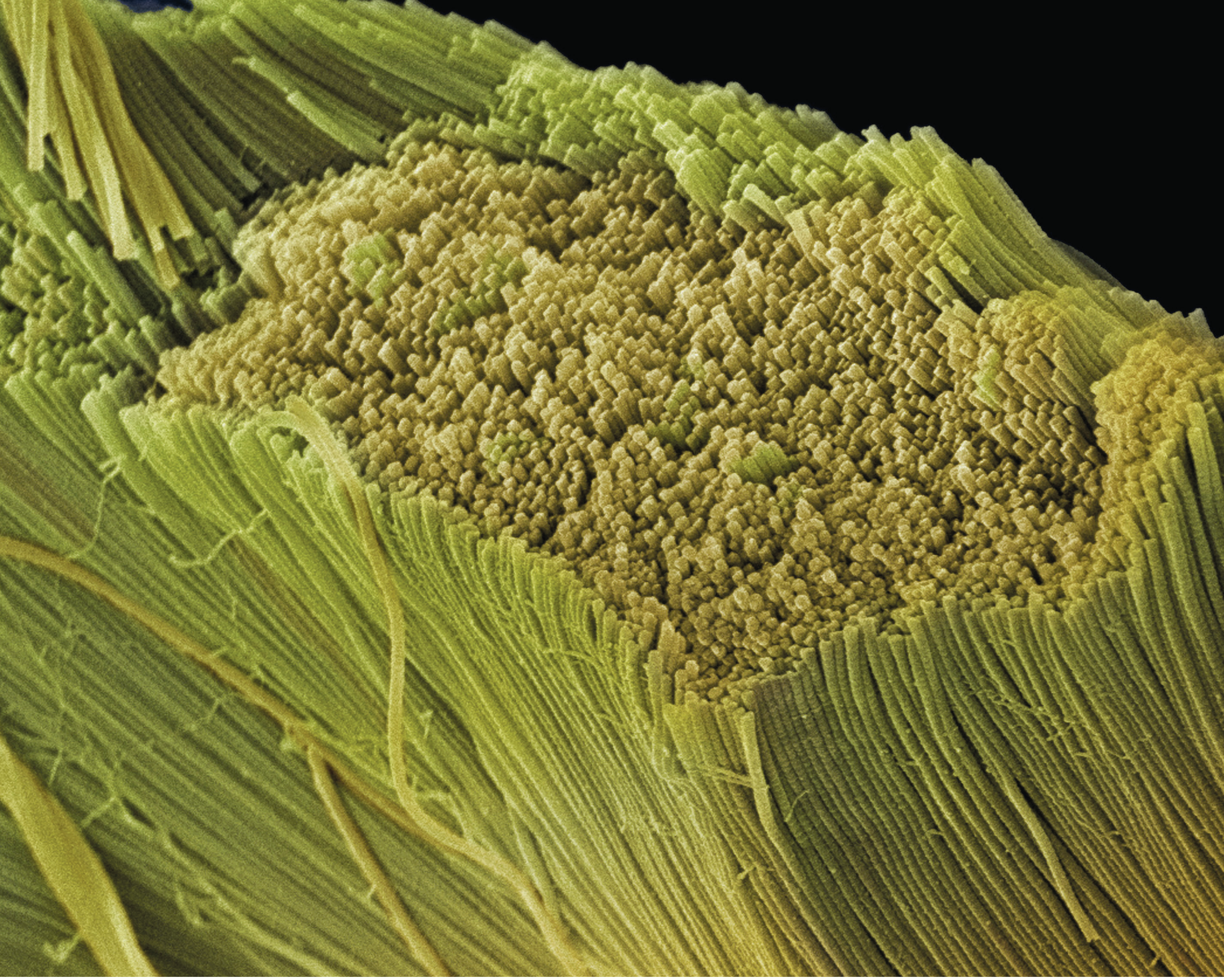
Different types of atoms in a bond don’t share electron density evenly. And when one of the atoms in a π-bond draws a disproportionate share of the electron density toward it, such as oxygen in a carbonyl group, the carbon atom sports a π-hole—a region of positive charge found in the clouds that make up the bread of the electron-density sandwich of the π-bond. For example, the structure of collagen—the most abundant protein in mammals, found in skin, cartilage, tendons, and ligaments—contains many carbonyl groups and therefore many π-holes. If you want to understand collagen, you need to know what those π-holes are doing.

**QUICK TAKE**

**Differing molecules have varying amounts** of positive and negative charge across their surfaces, and that variation affects their shapes and reactions.

**σ-holes and π-holes both present** an area of positive charge on a molecule’s surface, which can help researchers predict the particle’s behavior.

**Debate among chemists studying** these interactions can lead to advances that fuel the design of new drugs and materials based on these patterns.

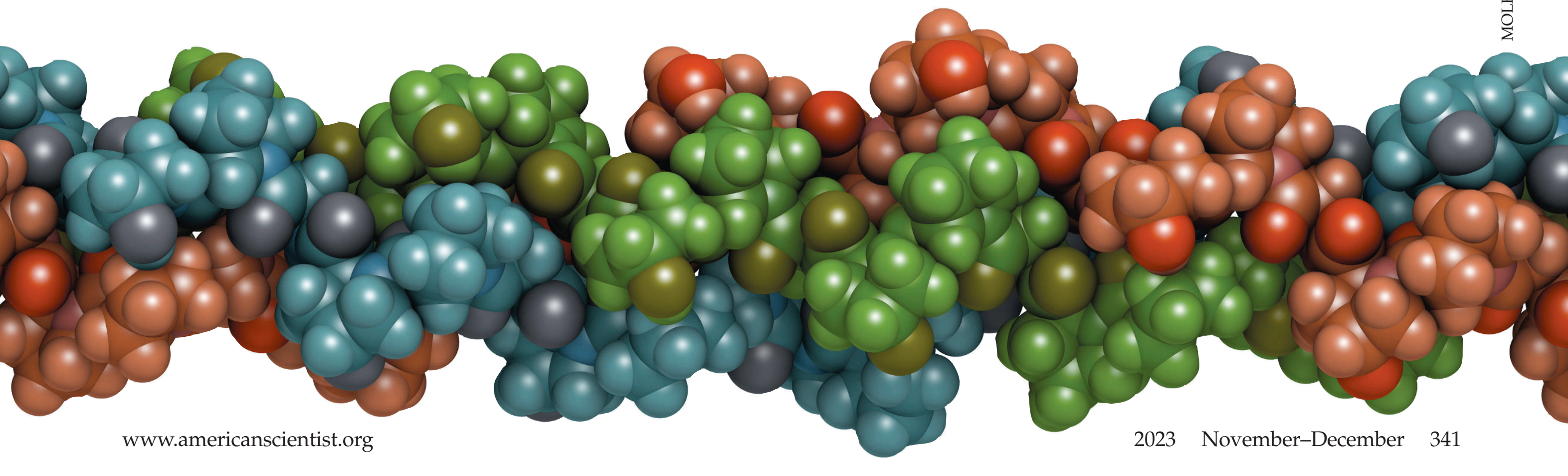


Steve Gschmeissner/Science Source

**Intertwined bundles of collagen provide structure to connective tissues that surround individual nerve fibers, as seen in this micrograph (*above*). π-holes help determine the structure of collagen and many other proteins. Collagen is formed from protein helices (*below*) that wrap around one another like analog telephone cords. Each helix is stabilized by π-hole interactions.**

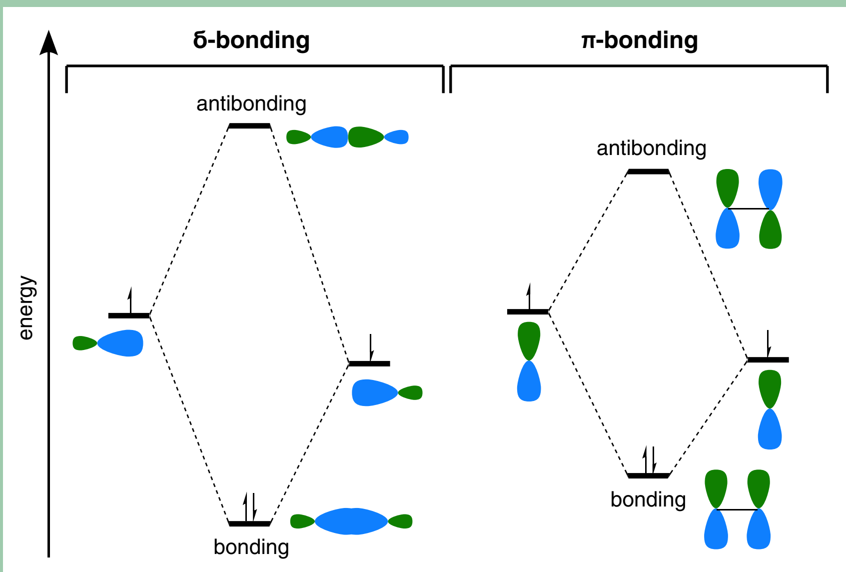
Chemists visualize the positively and negatively charged regions that a molecule presents along its exterior by computing *electrostatic potential surfaces,* wrapping the molecule in a brightly colored sleeve that shows regions of positive (blue) and negative (red) charge, including π-holes. In the figure at the bottom of page 342, blue is shown—corresponding to positive charge—near the carbon of the carbonyl group in each unit of collagen. This charge variation has implications for molecular shape. In collagen's 3D structure, for instance, three peptide strands coil around one another like analog telephone cords, with each

MOLEKUUL/Science Source



## σ and π Bonding

Charged surfaces are one way that chemists rationalize how a molecule's electrons shape its behavior. But chemists also think about orbitals, which are mathematical functions related to the probability of finding electrons in particular locations. In this concept, when two orbitals interact, they form two new orbitals that distribute the electrons more, resulting in one orbital that is lower in energy than the energy of either starting atomic orbital, and one that is higher. For all molecules discussed in this article, only two electrons are involved in these interactions, and these electrons both get to "reside" in the lower energy orbital, or *bonding orbital*, that results from the interaction. The higher-energy, more-delocalized orbital that results from the interaction is called the *antibonding orbital*, and because it is "empty"—no electrons reside in it—it does not hurt the energy of the molecule.

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individual strand forming a helix because the electron-rich carbonyl oxygen from one amide (N–C=O) is attracted to the π-hole of another amide carbonyl further down the strand.

With such maps, it sounds straightforward to predict how molecules should interact, but chemists argue about the nature of π-hole binding. The nature of intermolecular interactions is a long-standing issue in physical chemistry, but the focus on holes is a modern one. The plots of many π-hole surfaces show a lot of blue, suggesting that many regions of the molecule could be attracted to an electron-rich partner. Some argue that the region of positive electrostatic potential near a carbonyl shouldn't be considered a localized hole. And in some molecules, unambiguous holes in the electron density aren't actually attracted to electron-rich groups.

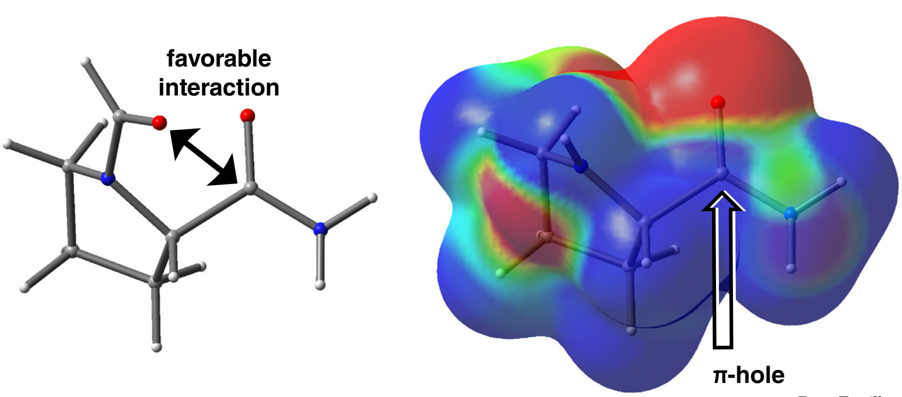
Getting to the bottom of these details might sound esoteric, but it is important for understanding how molecules are put together. It also has practical implications: If chemists understand how π-holes work, they can do a better job of predicting the outcomes of chemical reactions and designing new ones in areas from biology to industry.

**Collagen, the most abundant protein in mammals, contains many π-holes. If you want to understand collagen, you need to know what those π-holes are doing.**

### Digging into π-Holes

These unusual patterns of charge have inspired chemists to look deeply into the origins of the stabilization associated with π-hole interactions. Not surprisingly, deep dives have led to passion-filled debates. What are the bases of the arguments? First and foremost, electron density in a molecule is inherently spread out, albeit unequally, across the whole molecule, but chemists tend to want to carve it into chunks, in part because we have been trained to think of molecules as assemblies of functional parts. But electron density doesn't come in parts, so fragmenting it, while potentially useful, cannot be done in a single correct way. There is no consensus, and arguments, sometimes ferocious, about which fragments make the most sense, ensue.

Second, chemists frequently disagree about which physical factors contributing to attraction are most important. So far, we've talked about *charge–charge attraction* as being im-

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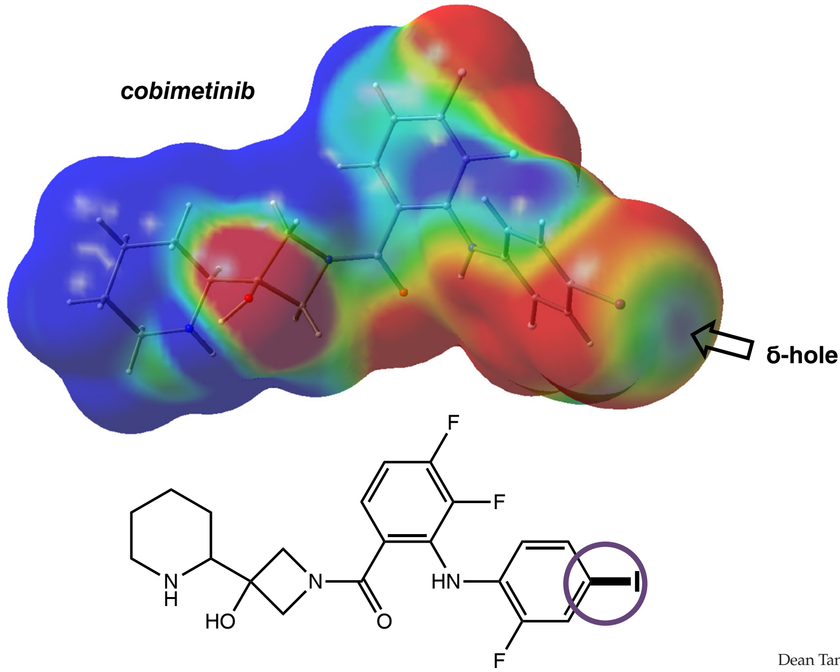
**This atomic-scale view of a peptide chain shows how an electron-rich oxygen from one amide group interacts with an electron-poor carbon from another further down the strand. These types of π-hole interactions stabilize protein helices, such as those within collagen.**

portant for holding collagen together. But another way to look at this question is through *molecular orbital interactions*. Molecular orbitals are another way to describe the electron smears within bonds—instead of defining them simply as volumes of charge, orbitals are wavelike mathematical functions describing the probability that an electron resides in a particular area. Electrons can act like waves as well as particles, which means that they can interfere with each other as they interact, both constructively and destructively. Constructive interference equals favorable molecular orbital interactions.



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**Cobimetinib—an anticancer drug—includes a bond (*circled*) between a benzene ring and an iodine atom. This bonding arrangement creates a σ-hole, an area of positive charge (*blue bull's-eye*) in this electron density map.**

Sometimes, the chemists involved only have eyes for their favorite contributors to bonding and binding. As one leader in the theoretical characterization of such interactions, the University of Richmond's Kelling Donald, says, they are feeling different parts of the same proverbial elephant without taking in the whole beast. Still, sometimes being focused can be useful.

Ron Raines's group at the Massachusetts Institute of Technology (MIT) has demonstrated through elegant laboratory and theoretical experiments that the interactions between amide groups described previously stabilize

**Even if chemists arrive at different models of how π-hole and σ-hole interactions work, these models can lead to testable predictions and drive new experiments.**

the 3D structure of collagen. Their description of π-hole binding is mostly based on favorable molecular orbital interactions, rather than on the charge-based model. Which is correct? Based on my experience, I would say that both effects contribute. And focusing on either aspect can be useful. For example, the Raines group and Mohammad Movassaghi's group, also at MIT, have applied what they've learned about π-holes to aid drug design, putting their orbital analysis of π-holes to use to tweak the structures of anticancer drugs so that they are more likely to remain stable in the body without losing their effectiveness.

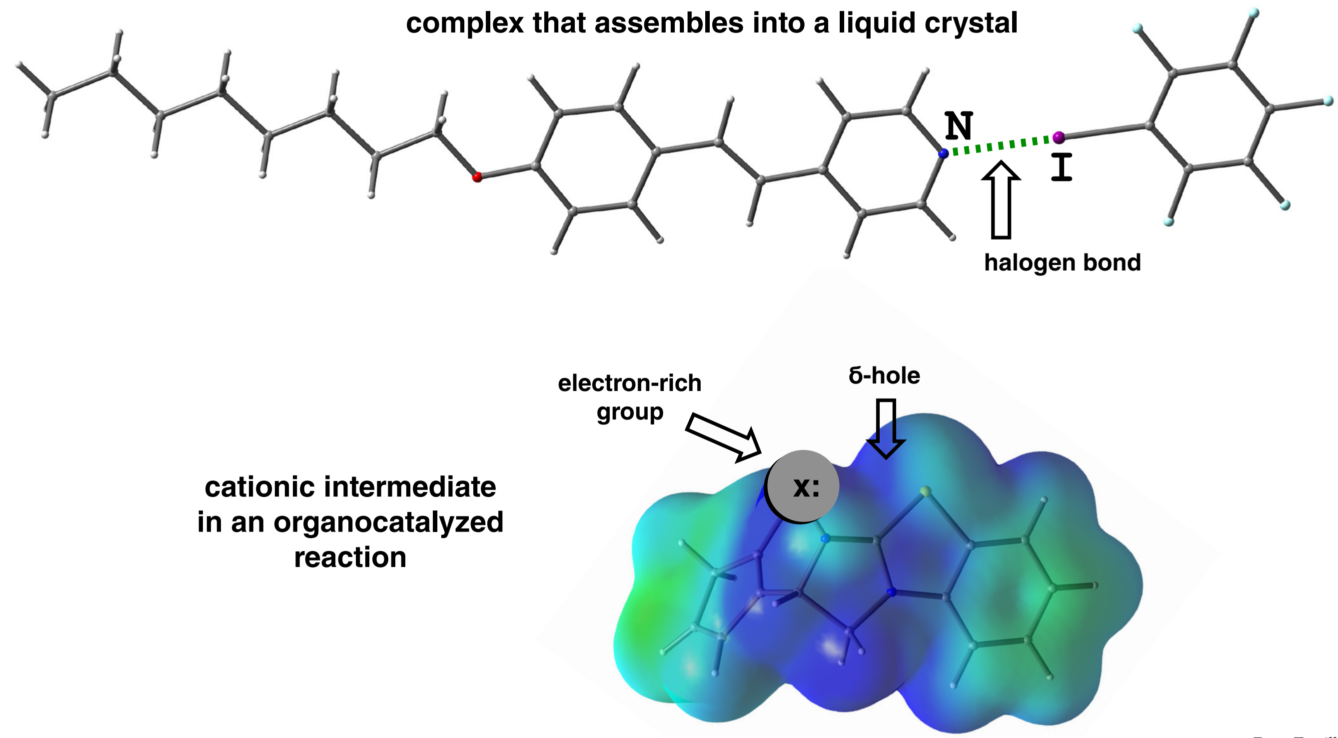
### Studying σ-holes

Like their π-hole cousins, *σ-holes* spark both arguments and opportunities for chemical innovation. Within a σ-hole, a region of positive charge is found along the line connecting two covalently bonded atoms, but not between the atoms, as in another anticancer drug called cobimetinib, used to treat certain types of melanoma.

Chemists have recognized the potential role of σ-holes in a range of binding patterns. They can determine the local preferred shapes of single molecules. They can help small molecules bind to large ones. They can hold molecules together in repeating patterns in crystals and liquid crystals. The poster children of σ-hole–containing molecules are the so-called *aryl halides* like cobimetinib—molecules in which halogen atoms, such as chlorine, bromine, and iodine, are attached to benzene (or related) rings. In x-ray crystal structures, such molecules often interact by pointing their carbon–halogen bonds at electron-rich atoms in other molecules. This type of σ-hole interaction has its own name: halogen bonding.

In the context of medicinal chemistry, electrostatic potential surfaces can be thought of as what a protein binding site "sees" when confronted with a drug. If the drug is a good match for the binding site, the binding site will look like a negative of this surface—a cavity of approximately the same size and shape whose surface charge distribution is opposite to that in the drug molecule. Cobimetinib offers a classic example of how a σ-hole within a drug molecule can facilitate that beneficial interaction, allowing it to bind to its target, a protein involved in the rapid proliferation of malignant cells.

The same arguments that arise over the origins of π-hole interactions also surface for σ-hole interactions, and for the same reasons: As much as we understand about the basic attractions and repulsions that drive chemistry, we still have much to learn about the subtle ways that electrons and charges control the shapes and reactivity of complex molecules. Even if different chemists arrive at different models of how π-hole and σ-hole interactions work, these models can be useful if they lead to testable predictions and drive new experiments that shape molecular and materials design.

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**Interactions that include σ-holes can stabilize both long-lasting and transient chemical structures. An electron-rich pyridine group (*that includes the N above*) interacts with the σ-hole of an aryl halide in a complex that assembles into a liquid crystal. Electron-rich groups (*lower image*) can interact with σ-holes in a reactive intermediate, a short-lived structure within a chemical reaction that determines a product's composition, connectivity, and shape.**

As Bernard Silvi from Sorbonne University in France wrote in a 2019 paper, "The origin of this dispersion of opinions is not a crisis of our discipline announcing the advent of a new paradigm but rather a consequence of its good health. . . . These systems of explanation . . . address different meanings of a given question and are intended for different scientific (sub)communities. Each system corresponds to its own representation of the microscopic matter, adopts its own point of view, and uses its own vocabulary."

Luckily, multiple viewpoints tend to spark future experiments, which should fuel better predictions about how changing molecules' electronic structure will affect the strengths of their interactions.

For example, both π-hole and σ-hole interactions have become part of the medicinal chemist's toolbox for rational drug design: the process of building new molecules that can counteract the effects of disease-causing proteins. As chemists catalog the geometries of interactions such as π-hole and σ-hole interactions through x-ray crystal structures of small molecules binding to proteins, they can predict the best orientations of the two partners participating in those interactions and attempt to understand the origins of their attraction using quantum mechanics calculations. But using what they learn from those quantum mechanics calculations (whether they reach a consensus or not), chemists can then derive simple mathematical equations that they can employ to rapidly predict how new, small-molecule drugs might bind to a target protein's binding site.

These strategies now propel molecular design of new drugs for diseases ranging from HIV to cancer that bind via σ-hole interactions, new polymers that hold themselves together using π-hole interactions, and more. Regarding this problem from multiple viewpoints, learning from each, and applying those lessons has helped chemists design new molecules and new experiments. So let's hope the discussion continues—let's keep those pie holes open.

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*Dean Tantillo loves to study the complexity associated with his young children and with the mechanisms of chemical reactions. He does both in Northern California, where he is a professor of chemistry at the University of California, Davis. Email: djtantillo@ucdavis.edu*

# How Herman Hollerith Counted America and the World

*In the late 1800s, the inventor designed a revolutionary punch-card tabulating system, a key moment in the development of modern computing.*

Ainissa Ramirez

In 1879, 19-year-old Herman Hollerith aimed to make a name for himself and wash off the stain of New York City poverty. His father had died when he was about 10. The tragedy not only shook his family to the core, but it also forced them to leave the comfort of their tight-knit enclave of German relatives in Buffalo, New York. It was there that his mother began making one-of-a-kind bonnets for sophisticated ladies. But after she was widowed, she became a full-time milliner. She moved her family to New York City, where she could reach more customers.

Herman was a sensitive boy, and the transition to New York City seemed to impact him deeply. When a spelling bee was announced at school, he jumped out of his classroom's second story window, choosing bodily harm over revealing his weakness in spelling. Fortunately, his astute mother recognized her youngest child's acrobatics as a call for help and hired a Lutheran minister to provide private tutoring. Under the clergy member's instruction, Herman's genius soared. He entered the Columbia University School of Mines at the age of 16, studying metals and mining. When he graduated with his Engineer of Mines degree in 1879, he posed for a photograph (*see figure at right*), donning an extravagant top hat and coat on his thin, barely six-foot-tall frame. His task now was to find work to match his ambition.

With a knowledge of metallurgy from his engineering degree, Hollerith landed a job as a Special Agent at the U.S. Census Office in Washington, D.C., writing reports on the use of water and steam power for iron- and steel-making. While at the Census Office, he also discovered that the United States government did not have a full idea about the granular makeup of its citizens. Additionally, Hollerith realized that the way the Census clerks scribbled numbers on paper seemed barely more advanced than Babylonian hatch marks in clay. He also watched as mountains of census forms were tallied by hand, taking up most of the decade and threatening to overlap with the following count.

Library of Congress Prints and Photographs Division

**In 1879, 19-year-old Herman Hollerith graduated from the Columbia University School of Mines. He soon landed a job writing reports at the U.S. Census Office, unaware of how it would influence the rest of his career.**

One evening at a party, Hollerith connected with one of the most prominent men working on the 1880 Census—John Shaw Billings, an esteemed physician and Army surgeon, who had created an unrivaled medical library and was in charge of the 5th Division of the Census on Vital Statistics. Hollerith admired Billings greatly, doing extra work for him by compiling life tables and graphs, in addition to the reports Hollerith already had to write. Sometime around 1879, Billings invited Hollerith over for tea. On that Sunday evening, the older man waxed poetic about the technology the Census needed. Billings had long been dissatisfied with how the Census was conducted and had been collecting information about individuals by storing key details on cards with well-placed small holes to mark information. Looking at the young and motivated Hollerith, Billings said, "There ought to be a machine to help tally all this information." Such an invention would

**QUICK TAKE**

**The 1880 U.S. Census took** seven years to complete. Seeing this glacial pace, a young, ambitious Herman Hollerith working at the Census Office began brainstorming solutions.

**Hollerith's tabulating system** used punch cards run through an electrical machine that compiled the data. A rough count for the 1890 Census was completed in six weeks.

**Hollerith's tabulators** were used to compile all sorts of data around the world for several decades. His company eventually merged with others to form IBM.

Division of Medicine and Science, National Museum of American History, Smithsonian Institution

**Hollerith invented a set of machines for compiling data for the U.S. Census. The system included a punch machine (*left*) for entering data about each person onto a blank card, a tabulator (*center*) for reading the cards, and a file box for sorting the cards (*right*). When a punched card was inserted into the metal contraption on the right side of the tabulator and the crank was pulled, it would complete a circuit and count the data points on the dials above the tabulator. This concept of punch-card tabulating would make its way later into modern computing.**

undoubtedly change how quickly the Census was counted, as well as save the government millions of dollars. In that moment, Billings planted a seed in the fertile soil of Hollerith's mind.

**Getting to the Punch**

Hollerith feverishly investigated how a tabulating machine might function, learning more about the Census's operation by taking on additional work in another part of the organization. After becoming knowledgeable about the current processes, Hollerith started to hatch an idea that he was excited to share with Billings. However, when Hollerith explained his new scheme, Billings wasn't interested in working with him to develop a machine. Billings just wanted the ready-made solution. Disappointed but not discouraged, Hollerith set off to explore how to count the entire U.S. population with a machine of his own design.

Hollerith learned all he could about one machine that had been used in the previous Census. Prior to that Census, clerks had tabulated by hand on tallying sheets. In 1872, Charles Seaton created a machine that looks like a modern-day pasta maker. Each ribbon of paper that was spit out was a tally sheet that pertained to a specific column of demographic data. The paper could then be advanced to a blank region, ready to receive new data. This invention was a step in the right direction, but it had many limitations, because it was essentially a compact tally sheet. Hollerith understood that a new machine was needed that not only collected data but also counted it.

To better understand this earlier invention, Hollerith spent all his free time in Washington soaking up as much as he could from Seaton. But soon Hollerith's appointment at the Census Office came to an end. He tried to find another job nearby. The best position he could find that gave him the freedom to tinker was a teaching position at the Massachusetts Institute of Technology (MIT). Most young men would be thrilled to be affiliated with such an institution, but Hollerith wasn't entirely convinced. He was reluctant to accept a pay cut. But after a former teacher from Columbia reminded him that one's salary was no measure of one's value, Hollerith took the job. Although his body was located in Boston (MIT's home before Cambridge), his mind never left Washington, D.C.

While teaching mechanical engineering at MIT, 24-year-old Hollerith spent all his free time working on his "Census Machine." His first attempt in 1882 used a strip of paper, like Seaton's device, with a hand punch and a reader. Holes were punched into the paper. A hole was registered in the reader by a pin hovering over its metal roller. When electronic contact was made, the

hole would be counted. But soon the shortcoming of this approach became obvious. With information stored this way, it was difficult to get to a specific file without unraveling the whole roll. Plus, Hollerith found that it took what felt like miles of continuous paper to store information about just a few people. He began to think there had to be another way to store information compactly and access it readily. Soon, his ideas moved away from using long strips of paper with holes to using cards with punched holes—a concept that dated back to his days at university.

The Art Institute of Chicago, Art Resource, NY

**Hollerith came up with the idea of using punch cards to tally census data after becoming familiar with their use in textile looms. The miniature model above includes a Jacquard attachment at the top, which used a series of punch cards to program each thread individually. This system could replicate complex weaving patterns.**

When Hollerith had attended Columbia, he lived with his older sister Bertha Meyer and her husband Albert. Albert worked in the silk industry and tried his best to convince his young ward to join him in textiles. Hollerith had a strong mechanical sense, and the textile industry had many opportunities that might have suited him. But he also loved the practical uses of science, such as the chemistry of beer, about which he presented for the Chemical Society while still a student at Columbia in 1878. Textiles did not fully align with Hollerith's temperament, so he didn't take up his brother-in-law on the offer. But Hollerith saw something in the textile factory that never left him.

One day, Meyer showed young Hollerith a special loom that created complex pictures and lace designs, getting directions from punch cards. Decades earlier in the 1800s, Joseph Marie Jacquard had invented this loom in France. The holes in the cards allowed long weaving hooks to pass, creating an image line by line. Where holes were absent, stitches were not made. These Jacquard looms were all over France and had migrated to Europe and later to the United States. Years later, Hollerith would realize that the way these cards stored information for weaving might also store information for the Census.

In 1883, Hollerith left MIT and returned to Washington, D.C., to find work. As he continued work on his "Census Machine," he realized he needed to know everything about writing a successful patent, so he decided to get a position at the U.S. Patent Office. Then, after about two years, he quit and worked for himself as an "Expert and Solicitor of Patents," assisting other inventors with writing these legal documents for a fee.

**Hollerith designed an electricity-based brake system at a time when Thomas Edison was bringing incandescent bulbs to the world.**

### From Concept to Prototype

Hollerith continued to tinker on his invention and ended up spending all of his income on his creation. When he wasn't working on it, he was meeting officials at the Census Office, reporting on his progress to them. One day, these officials invited him to demonstrate his model, but the machine wasn't quite ready for full-scale use. To get the invention where he needed it to be, Hollerith required money to build a robust version as well as funds for the patent filing fee. This plan felt foolproof to him, which is why he pleaded for additional funding from Meyer, imploring to his brother-in-law in a letter that he was no longer working on a "crude machine." But Meyer wasn't convinced, and the money never came. When Hollerith asked other family members for funding, legend has it that they laughed. Desperate, Hollerith attempted to find other ways to come up with the money. He soon looked toward the railroads.

Since the end of the Civil War in 1865, the amount of railroad track in the United States had been growing rapidly, and the railroads were becoming America's biggest industry, guaranteeing a pot of gold for any inventor who could create a useful technology for trains. Hollerith combed through railroad journals seeking opportunities to build something, and he found that there was a competition in Iowa hosted by the Master Car Builders, scheduled for 1887. The contest involved designing a better braking system. At that time, brakes were crude, and many passengers feared bodily harm even riding trains. With nothing to lose, Hollerith tossed his hat in the ring.

Five brake systems were tested in the competition: three using compressed air, one using vacuum, and Hollerith's using electric brakes. Hollerith designed this electricity-based brake system at a time when Thomas Edison was bringing incandescent bulbs to the world. Hollerith won in the competition but he also lost. His train stopped three seconds faster and 128 feet (39 meters) sooner than the air brakes. Also, his system didn't jolt passengers. But in the end, the judges were uncertain about how electric brakes would operate during a thunderstorm, not to mention that many superstitions still existed about electricity. So the judges gave the prize to the air brake system made by a popular inventor named George Westinghouse,

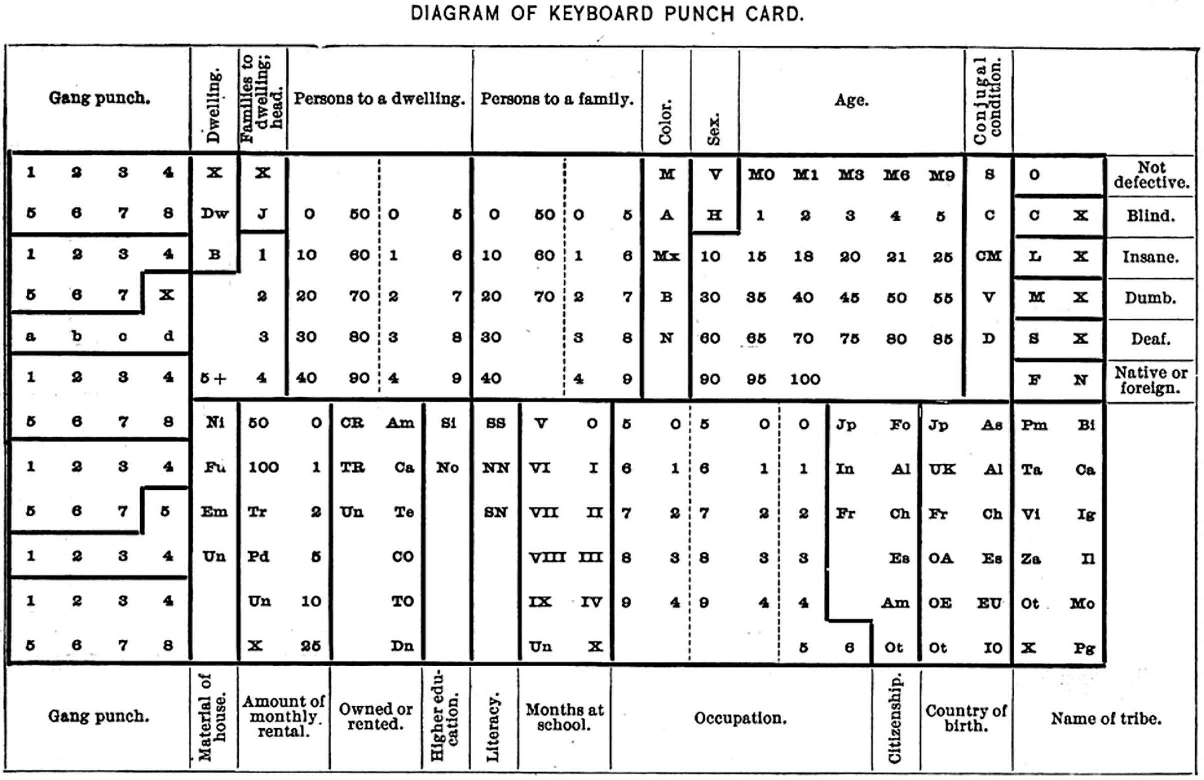


DIAGRAM OF KEYBOARD PUNCH CARD.

| Gang punch. | | | | Dwelling. | Families to dwelling; head. | Persons to a dwelling. | | | | Persons to a family. | | | | Color. | Sex. | Age. | | | | | Conjugal condition. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | X | X | | | | | | | | | M | V | MO | M1 | M3 | M6 | M9 | S | O | | Not defective. |
| 5 | 6 | 7 | 8 | Dw | J | 0 | 50 | 0 | 5 | 0 | 50 | 0 | 5 | A | H | 1 | 2 | 3 | 4 | 5 | C | C | X | Blind. |
| 1 | 2 | 3 | 4 | B | 1 | 10 | 60 | 1 | 6 | 10 | 60 | 1 | 6 | Mx | 10 | 15 | 18 | 20 | 21 | 25 | CM | L | X | Insane. |
| 5 | 6 | 7 | X | | 2 | 20 | 70 | 2 | 7 | 20 | 70 | 2 | 7 | B | 30 | 35 | 40 | 45 | 50 | 55 | V | M | X | Dumb. |
| a | b | c | d | | 3 | 30 | 80 | 3 | 8 | 30 | | 3 | 8 | N | 60 | 65 | 70 | 75 | 80 | 85 | D | S | X | Deaf. |
| 1 | 2 | 3 | 4 | 5+ | 4 | 40 | 90 | 4 | 9 | 40 | | 4 | 9 | | 90 | 95 | 100 | | | | | F | N | Native or foreign. |
| 5 | 6 | 7 | 8 | Ni | 50 | 0 | CR | Am | Si | SS | V | O | 5 | 0 | 5 | 0 | 0 | Jp | Fo | Jp | As | Pm | Bi | |
| 1 | 2 | 3 | 4 | Fu | 100 | 1 | TR | Ca | No | NN | VI | I | 6 | 1 | 6 | 1 | 1 | In | Al | UK | Al | Ta | Ca | |
| 5 | 6 | 7 | 5 | Em | Tr | 2 | Un | Te | | SN | VII | II | 7 | 2 | 7 | 2 | 2 | Fr | Ch | Fr | Ch | Vi | Ig | |
| 1 | 2 | 3 | 4 | Un | Pd | 5 | | CO | | | VIII | III | 8 | 3 | 8 | 3 | 3 | | Es | OA | Es | Za | Il | |
| 1 | 2 | 3 | 4 | | Un | 10 | | TO | | | IX | IV | 9 | 4 | 9 | 4 | 4 | | Am | OE | EU | Ot | Mo | |
| 5 | 6 | 7 | 8 | | X | 25 | | Dn | | | Un | X | | | | | 5 | 6 | Ot | Ot | IO | X | Pg | |
| Gang punch. | | | | Material of house. | Amount of monthly rental. | | Owned or rented. | | Higher education. | Literacy. | Months at school. | | Occupation. | | | | | | Citizenship. | Country of birth. | | Name of tribe. | | |

Google Books

**Hollerith's tabulating system came to be used in censuses around the world. For example, this punch card was used in the Philippine Census of 1903.**

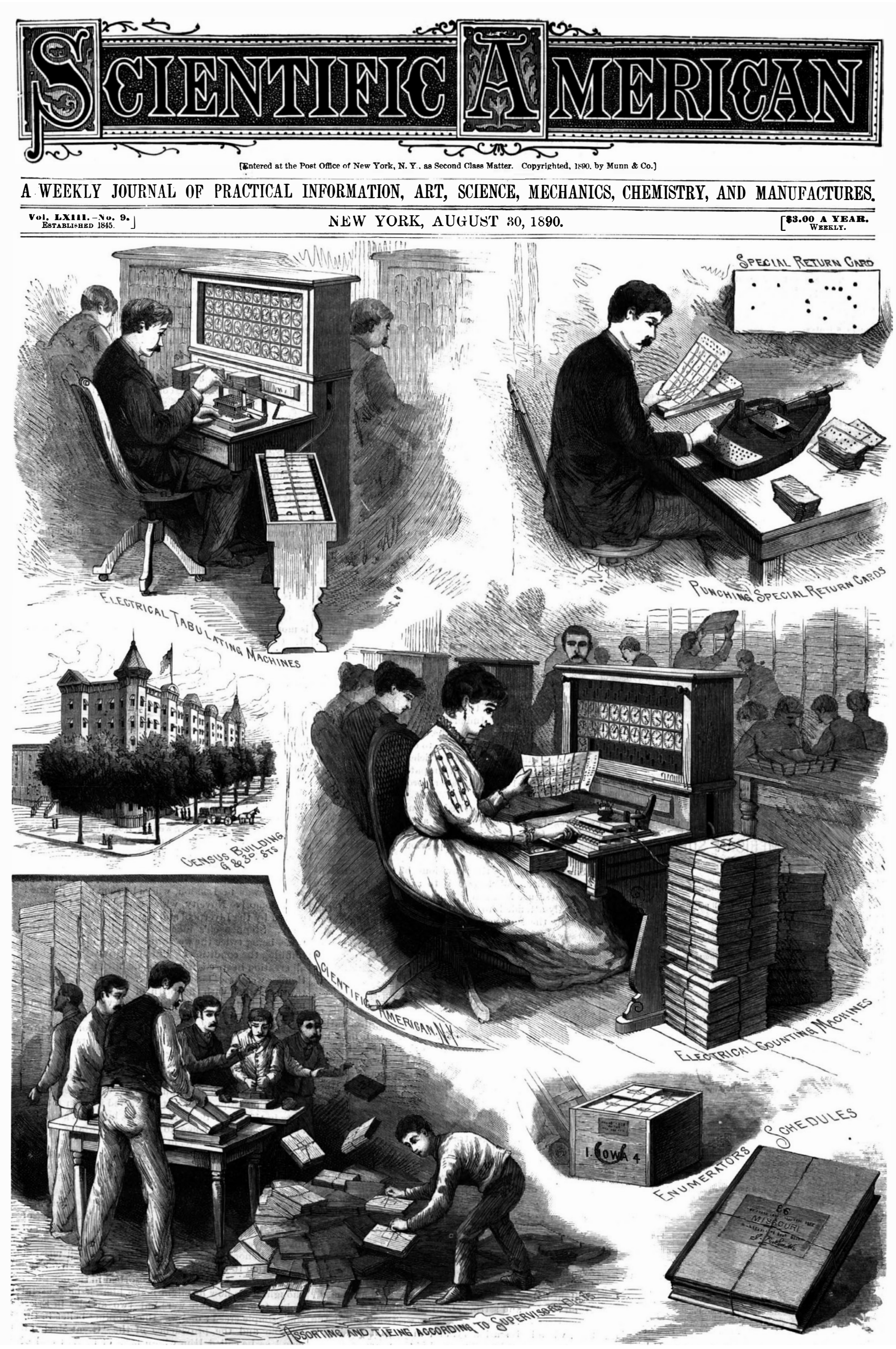
who already had a number of inventions in service in the railroad industry.

This loss stung Hollerith deeply, and, according to his biographer Geoffrey Austrian, he barred people around him from mentioning the name "Westinghouse." But Hollerith's luck would soon turn around. The City of Baltimore was desperate to efficiently collect their mortality statistics (such as causes of death) and contacted Hollerith, probably after hearing about his work from Billings. In 1887, this city that birthed America's national anthem also ushered in a new age of data by using Hollerith's punch-card tabulating machine to acquire information about its citizens—both the quick and the dead. When collecting such information, Hollerith used cards inspired by train tickets, where a conductor punched holes describing the rider, such as light hair, dark eyes, or long nose. These "punch photographs" helped identify and verify passengers. Hollerith initially used a conductor's punch, too, but after perforating 1,000 cards in one day, each with multiple holes, his arm was too sore for a repeat performance. These aches and pains inspired him to devise a machine with a lever inside to punch the cards; like a seesaw with a well-placed fulcrum, it required much less force on the hand.

Hollerith succeeded in Baltimore, and soon other opportunities materialized. The health departments of New Jersey and New York City sought his services and had both adopted his system by 1889. Hollerith's system was able to tabulate health-related statistics in a fraction of the time that the task took by hand, which was a great achievement. But his eyes were still set on the Everest of data he wanted to conquer—the next U.S. Census, happening in 1890.

NARA/Science Source

**An operator reads census forms and punches holes into dollar-bill-sized cards in a pattern that represents the data.**




*Scientific American* Archive; Computer History Museum

**Hollerith's invention was featured on the cover of *Scientific American* on August 30, 1890. Illustrations show various steps in the census tallying process. The previous year, Hollerith's tabulator had won a gold medal at the World's Fair in Paris.**

**Speeding Up the Census**

Until 1880, counting the number of citizens in the United States happened at a glacial pace. There were 26 questions on the 1880 Census, which captured information such as gender, place of birth, race, marital status, occupation, ability to read or write, and disability status. But there was no way to sift or sort all that data to know the number of persons in any combination of the categories. Hollerith designed an entire punch-card system that allowed the Census to not only count the total population, but also to separate them into smaller demographic groups, providing the nation with a mirror to know itself.

At the time that Hollerith was working on his system, other inventors were coming up with their own solutions. The Census Office had a competition of statistical machines, in which three competitors compiled data of 10,491 people living in four districts of St. Louis, Missouri. One system made by William C. Hunt recorded information about each person on slips of paper that were counted by hand; another system by Charles F. Pidgin was a modification of the first, using different colored paper, called chips, that were also sorted and counted by hand. This time, Hollerith was the competition's clear winner. Neither of these manual methods of slips or chips could keep up with Hollerith's machine, which worked in nearly half the time to translate the data onto cards, and one-tenth of the time to tabulate the information.

**The 1890 Census and Beyond**

When the U.S. Census of 1890 began, Hollerith's moment had finally come. Now 30 years old, Hollerith saw his automated tabulating punch-card system fully actualized. First, Census employees traveled door-to-door, taking down details about members of a household. Armed with forms containing nearly 30 questions, they scribbled down the information or in some cases directly punched that information onto a card. If a mistake was made on a card, the hole was patched with a small adhesive cover. Literal tons of paper forms were then returned to the Census Office, where the data were translated into holes punched into cards, with a keyboard that neatly pierced them, readying the card to be counted.

Next, the information on the card was tallied by a clerk sitting at the tabulation machine, which resembled an upright piano with counters distributed in rows and columns on its upper panel. At the location of the piano keys sat a small press, which looked like a square waffle iron with a medieval bed of nails coming from the top. If the nail passed through a hole in the card when the clerk pressed down, the nail completed an electrical circuit, sending current to a specific electronic counter. The counters looked like clocks, but instead of 60 minutes, they had 100 divisions. A long hand, like the minute hand, moved one division to count "one." The shorter hand, like the hour hand, moved one division to count "hundreds." If the nail did not pass through a hole in the card, the counter didn't move. After each card, the clerk lifted up the press, ready to count the next. Stacks of cards as high as the Washington Monument were tabulated every day.

U. S. National Archives Records Administration

**Hollerith's tabulating machine changed the way populations were counted. The census was not only a way for the country to know itself, it also reflected the times. Employment in the federal government was segregated until 1947. This photograph from the 1940s shows African American punch-card operators from the Census Office. They were part of the workforce of 2,400 punch-card operators that entered 328,341,293 cards for the census.**

The 1880 Census, conducted before Hollerith's invention, had taken nearly seven and a half years to complete. In 1890, a rough count of the entire U.S. population was performed twice in six weeks. According to the current Census historian, it took approximately two to three years to fully process and tabulate all the various Census subjects.

Soon, other countries came clamoring for this technology. Hollerith applied his automated census machines to counting populations in Austria, Canada, Russia, Cuba, Puerto Rico, and Norway. The results allowed these countries to get a clearer picture of themselves, too.

**The 1880 Census, before Hollerith's invention, had taken nearly seven and a half years to complete.**

In 1890, the same year as his Census triumph, Hollerith received a doctorate from Columbia for his electric tabulating system. By 1896, he formed the Tabulating Machine Company and would go on to secure a contract for the 1900 Census. The Census of 1910 also seemed like a sure deal, but the Census Office didn't want to pay Hollerith's fees. One of Hollerith's former employees quickly seized this opportunity by using Hollerith's plans to make his own machines. Hollerith knew this employee well, having given him loans to buy a home and to help him with the care of a sick child. The betrayal cut deeply, but it forced Hollerith to look into new markets and provide new services for businesses and industry, such as accounting, recordkeeping, and statistical analysis.

Soon, Hollerith had other customers, such as George Westinghouse (a name he had once vowed never to utter) and the Marshall Field's department store, as well as electric companies, insurance companies, steel manufacturers, and railroads. Later, Hollerith's business would merge to form a new entity called the Computing-Tabulating-Recording Company (C-T-R). That company was eventually folded into a newly formed company, called International Business Machines (IBM), bringing Hollerith's punch cards—and a new way to store data—to every corner of the world.

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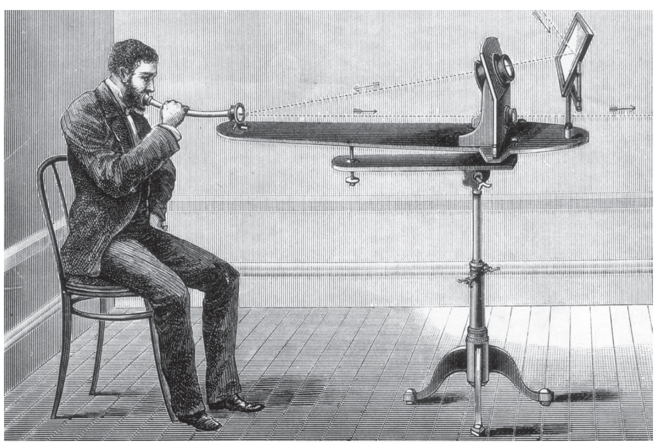
# “Seeing” into Opaque Materials with Light and Sound

*Lasers generate and detect ultrasonic waves that can image the interiors of solid objects.*

David M. Pepper and Todd W. Murray

People have always been fascinated by things that are hidden from view, and by what might be found inside opaque objects. We see objects because some of the light that strikes them is reflected and eventually enters our eyes. However, not all of the light is reflected from the surface; part of it is absorbed. Is there anything useful that can be done with this absorbed light to see within the object? The answer lies in a serendipitous observation made more than 140 years ago by Alexander Graham Bell when he heard sounds produced by light falling on an opaque object.

Bell was working on one of his more intriguing inventions, the *photophone*. It used sunlight, instead of wires, to carry voice information between two individuals. The sunlight was modulated by the voice of the speaker and was converted to electrical signals at the other end with a detector made from selenium. This invention was similar in principle to today’s fiber-optic communication, except that Bell did not confine the light to a fiber. In the process of his experimentation with the photophone, Bell discovered that it was possible to hear the sound by simply placing his ear in the air close to an object that was illuminated by the light—no electrical connections were necessary. What Bell heard was the result of the formation of sound waves by the rapid thermal expansion and contraction of the air over the periodically heated surface, which is now referred to as the *photoacoustic effect*. His observation was the basis for a novel technology using lasers that now enables us to see into the interiors of opaque objects without ever touching them.



Science History Images/Alamy Stock Photo

**The *photophone*, a less well-known invention of Alexander Graham Bell, used sunlight to carry voice information. Bell observed what is now called the *photoacoustic effect*, the generation of sound waves by the rapid expansion and contraction of air over a heated surface.**

The physical phenomena involved in Bell’s experiment are considerably more complicated than he realized at the time. When light is absorbed at the surface of a solid, the result is the generation of heat-induced surface temperature changes, leading to pressure-density waves, or acoustic waves, in both the air and the solid. (The principle is approximately the same as what causes the vanes to spin in a small whirligig device often used in school science classes, called a light mill or a Crookes radiometer.) Periodic vibrations that propagate within the material create *compressional sound waves*. But in the solid, an additional kind of sound wave, called a *shear wave*, involves motion of the atoms in a direction transverse to the direction of propagation, but without any associated temperature change. All are potentially useful for subsurface imaging because they can scatter and reflect from internal elastic features, producing “echoes” that return to the surface with information about those features. By measuring the tiny vibrations on the object’s exterior caused by these effects, one can locate the back wall of the object or see an otherwise hidden defect inside it, such as corrosion in an airplane, cracks in a weld, defects in red-hot steel coming out of a mill, or voids in 3D printing, as well as visualize microstructure evolution in uranium-zirconium nuclear fuel alloys, blood vessels in the eye, or tumors in the body.

**QUICK TAKE**

**Opaque objects that are illuminated** do not reflect all of the light that hits their surfaces; some of the light is absorbed and can create vibrations within the material.

**Lasers can both create and detect** ultrasonic wave signals, which are modified by defects or other structures inside the opaque material and produce a measurable signal.

**Peering inside opaque materials** without touching or damaging them is useful in manufacturing inspection, infrastructure monitoring, landmine detection, and medical imaging.


Courtesy of Tecnar

**A red-hot stainless steel tube passes under a laser ultrasound inspection system directly after leaving a furnace. A pulsed laser generates ultrasound in the pipe, which reflects within its walls and then is measured by a second laser setup. This noncontact system provides immediate feedback for quality control. Laser-based ultrasound can be used to image the interiors of a variety of opaque materials, from aircraft components to human eye tissue.**

## Optical Detection

Because the effects of subsurface elastic features show up as vibrations of the surface, they can be detected optically. Thus, light can indeed be used to see the interior of an otherwise opaque object, without making any physical contact. The process is called *laser-based ultrasound*. Pulsed laser beams "ping" the object to generate high-frequency sound waves, which are detected by low-power lasers that remotely sense the mechanical vibrations on its surface. One can view this process as being a form of sonar.

The subtle vibration patterns detected by these optical methods can reveal features buried beneath the surface of the object. These features include the thickness of the sample, hidden cracks, delaminations, voids, disbonding, and material inhomogeneities.

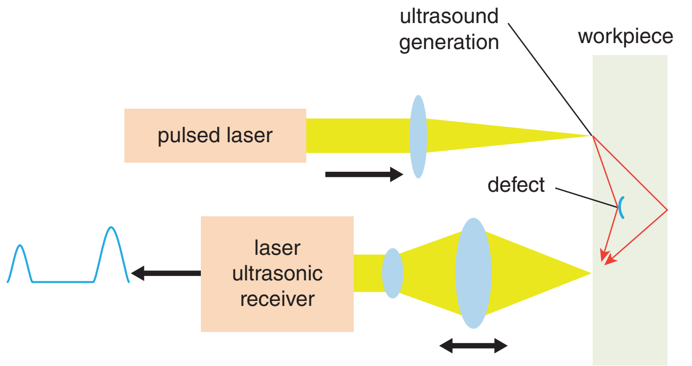
The ability to use echo ranging allows, for example, for in-process monitoring of the dimensions of manufactured parts, which, with real-time feedback control, can result in a higher yield of products that are within specifications. The noncontact, light-based method can be used, for example, to inspect aircraft for subsurface corrosion, microcracks near rivets, or degradation to the coatings of turbine engine blades.

Light-based inspection systems can be applied on size scales ranging from aging infrastructure (bridges, buildings, railways, aircraft, and naval vessels) to semiconductor microchips, wafers, or objects produced by 3D printing (also called *additive manufacturing*). For many applications, it is crucial that the measurement be entirely optical, either because the objects are otherwise inaccessible, or because there is a need for extreme cleanliness. For example, by using the remote capability of optical probes, one can inspect parts moving along an assembly line without interrupting their progress along the line. Also, because light probes do not require fitting a transducer to the surface, objects with irregular shapes can be inspected, such as composite sections of automobiles or jet aircraft components. Moreover, these probes can be configured to inspect parts in vacuums (such as outer space), in radioactive environments, or in other adverse conditions where one cannot easily reach the part or when it is impossible to contact the part during manufacture. For instance, laser ultrasound is used to measure the thickness of rapidly moving red-hot seamless steel tubes as they exit the furnaces of steel mills (*see figure above*).

## Light into Sound

When pulsed laser light is absorbed by an opaque object, a pulse of sound is generated. To create frequencies in the ultrasonic range (hundreds of thousands to trillions of cycles per second), short laser pulses are required: Pulse times range from tens of microseconds to less than picoseconds. The energy in the optical pulse is in the range of tens of millijoules, which is equivalent to the energy of a U.S. penny dropped from a height of 40 centimeters. Thus, the opaque object is "pinged" by the optical pulse.

Laser-based ultrasound can be generated using either of two optically induced mechanisms: the *thermoelastic*




Adapted from Y. Cheng, et al., *Sensors* 13:16146.

**In a basic laser-based ultrasound system, the short-pulse laser generates bulk and surface acoustic waves. These ultrasonic waves (*red*) scatter from internal defects, and also reflect from the back side of the opaque workpiece, resulting in surface vibrations that can be probed and detected by a laser ultrasonic receiver located on the surface. The signal output (*blue waves*) will be affected by the scattering from defects within the material, providing a means of detecting flaws or other subsurface characteristics.**

*effect* or *ablation*. In the former case, the opaque material is rapidly heated at laser intensities in the range of hundreds of kilowatts or more per square centimeter. The resulting high-frequency thermoelastic expansion launches the ultrasonic waves, as was first demonstrated in 1963 by Richard M. White, an electrical engineer at the University of California, Berkeley. In this case, the material is not modified or damaged; it returns to its initial state, unaltered.

The second mechanism, laser ablation, involves applying intensities of tens of millions of watts or more per square centimeter over a small area of the surface. This results in surface temperatures of thousands of degrees over time periods of 10 billionths of a second. The intense heating causes a small amount of material to be blown away from the surface, with the recoil of the surface generating an intense compressional sound wave.

The patterns of the ultrasonic beams that propagate into the object depend on what excitation mode is used, which in turn depends on the geometry of the part and the type of inspection needed.

In both cases, sound waves reflect from internal features within the object, whose elastic properties are different from those of the surrounding material. Ultrasonic echoes from these features can be reflected back to the surface (the mechanism is analogous to sonar). These reflected waves cause surface displacements that are exceedingly small, usually in the range of one-tenth of a nanometer to 10 nanometers. By comparison, a single atomic layer is about a third of a nanometer thick.

**The optical pulse "pings" the opaque object with an energy equivalent to that of a U.S. penny dropped from a height of 40 centimeters.**

### Signal Received

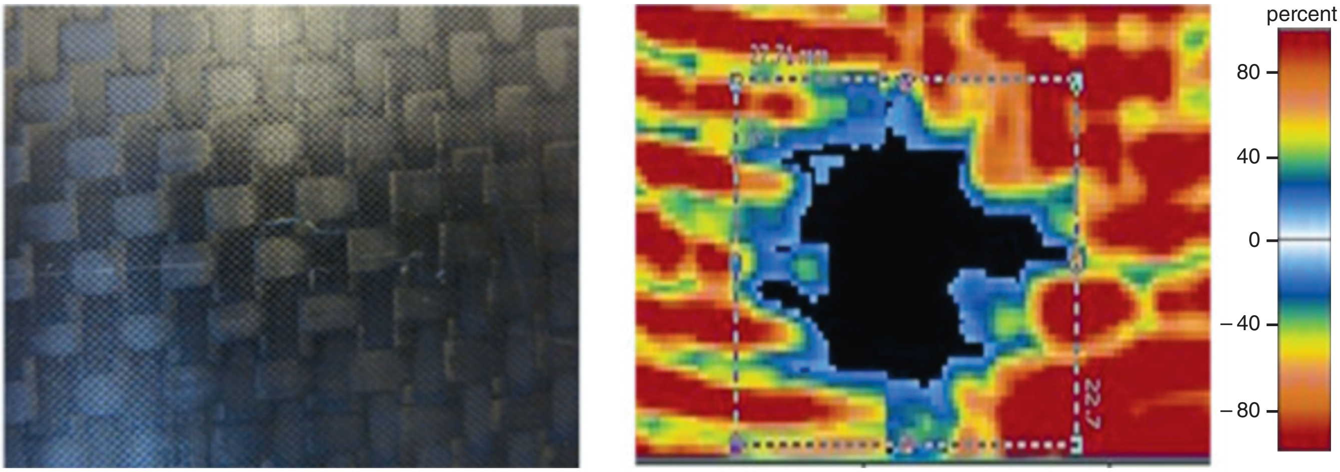
A second, low-power continuous operating laser, or a long-pulse laser, probes the surface of the vibrating object and, like what happens in radar, can sense the Doppler-shifted light as it reflects from the surface into the detector. The frequency of the probe beam is modulated by the surface vibrations, and it is these minute vibrations that contain the desired ultrasonic information. The speed of the vibrating surface is only about 10 centimeters per second during a typical ultrasonic pulse. Taking this measurement is very challenging: It's akin to measuring the speed of a crawling infant over a time period of only 100 millionths of a second.

Such detection sensitivity usually requires laboratory conditions, but this technique has to function in adverse environments such as a factory. To achieve this sensitivity, an *optical interferometer* is added into the process, between the vibrating surface and the optical detector. A typical optical interferometer comprises several high-quality mirrors and beam splitters to create two optical beams that combine (or interfere) at the detector. When one beam is shifted in space or frequency relative to the other beam, it produces an output change at the detector. In this case, the ultrasonic signal wave gives rise to this minute change, which can be one part in 10 thousandths of an optical wavelength (or equivalently, 10 billionths of a centimeter).

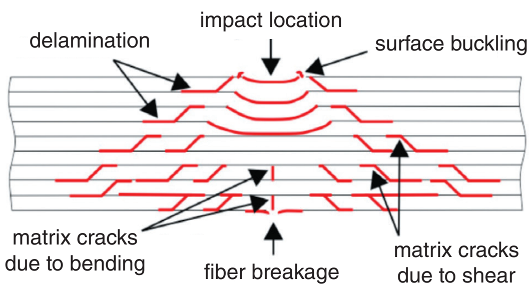
The mirrors used in laboratory interferometers typically have a surface roughness that is no more than a fraction of an optical wavelength. However, the surface of the reflecting object, such as an airplane fuselage or a welded part, can have a surface roughness that is thousands of times greater than that. A probe laser beam that reflects from such an unpolished surface will scatter over large angles into a pattern of laser spots, called *speckle*, which is deleterious to sensitive detectors.

Furthermore, low-frequency mechanical vibrations in a hangar or factory setting can have amplitudes in the range of a millimeter or so, one million times greater than the ultrasonic surface displacements to be detected. This combination of surface roughness and vibrations would render most interferometers useless as sensors.

To overcome surface roughness and vibration difficulties, in the 1980s physicist Jean-Pierre Monchalin of the National Research Council of Canada developed a novel scheme, based on an interferometer invented by French physicists Charles Fabry and Alfred Pérot at the outset of the 20th century. The probe laser light reflected from the vibrating sample enters this interferometer and bounces back and forth between a pair of partially silvered, fixed mirrors that face each other. This device acts as an optical resonator, with sharp peaks in the frequency of the transmitted light (analogous to resonant acoustic modes in a hollow tube). Adjusting the frequency of the laser to remain on the maximum slope of one of these resonance peaks makes the device sensitive to the small shifts in the frequency of the light reflected from the vibrating surface. This detec-




Top: From I. Papa, et al., *International Journal of Lightweight Materials and Manufacture* 4:37. Bottom: From T.-W. Shyr, et al., *Composite Structures* 62:193.




**Impact damage can result when a blunt object strikes the exposed surface of a fiber-reinforced polymer composite material. Sometimes the exposed surface shows no signs of damage (*above left*), but the impact may nevertheless have caused internal delamination, matrix cracking, fiber breakage, or perforation (*lower left*). Such impact to aircraft, for instance, can result from hail, bird strikes, runway debris, or tools dropped during maintenance. Laser-based ultrasound generation can reveal the hidden subsurface impact damage via ultrasound spurious reflections (*above right; color scale indicates the strength of the returned signal*). In this case, detection was aided with *squirter sensing*, in which a water-jet coupler contacts the test part and guides the ultrasound along the stream.**

tion technique is similar to tuning in to FM signals on a car radio, which use the resonance peak of an electronic circuit to demodulate that signal. The concept is also similar to that underlying gravitational-wave optical detectors, except in that case, the mirrors move in response to a gravity wave instead of a surface vibration.

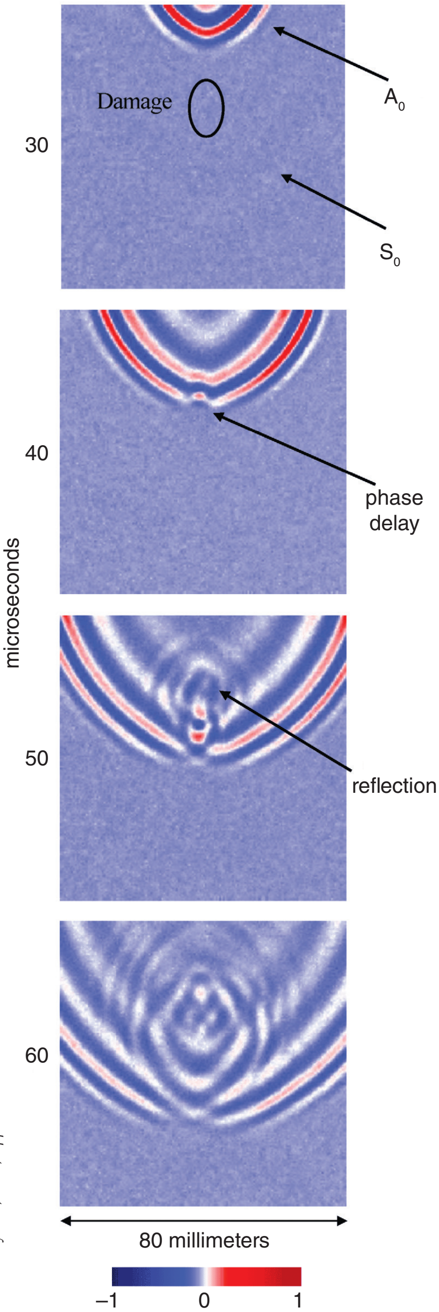
Another class of laser ultrasound receiver is referred to as an *adaptive interferometer*, which is sensitive to the minute vibrations of a mirror—in this case, the part undergoing inspection. This interferometer, called a *two-wave mixer*, was also invented at the National Research Council of Canada by Alain Blouin, Monchalin, and their colleagues, in the 1990s. It uses a photorefractive crystal to optically process two input laser beams. One beam is a reference wave, called a *local oscillator*. The second beam is the light that scatters from the unpolished, vibrating part undergoing testing, called a *signal beam*. This latter beam contains the ultrasound information to be detected. Both beams combine (or interfere) to form a real-time, or *dynamic*, hologram in the crystal. The hologram matches the wavefronts of the reference beam to those of the signal beam to compensate for surface irregularities. It is also referred to as an *adaptive photodetector* because it tracks the signal beam in time to account for workplace vibrations. The pair of matched beams then hit an optical detector, with its electrical output revealing the ultrasound signal. This technique functions in the same way as laser communication systems, which, by using adaptive optics, can detect low-level signals that have passed through turbulent atmospheres.

A third class of optical interferometer is sensitive to the medium itself between the mirrors: air. When sound waves travel across the interferometer, they create minute pressure/density waves in the air within the interferometer. The changes in density result in changes to the refractive index of the air, which in turn affects the optical output of the interferometer. One can view this system as a very sensitive microphone. The basic concept of this type of optical interferometer was developed and demonstrated in the late 2010s by physicists Balthasar Fischer at the Vienna University of Technology and Wolfgang Rohringer and his colleagues at XARION Laser Acoustics in Vienna, Austria.

## Checking for Flaws

Once the difficulties with detection sensitivity were resolved, laser ultrasound began to be used in a variety of applications. Using an adaptive interferometer, laser-based ultrasonic signals, sensed at a distance of about 1 meter, have been used to provide real-time, in-factory determinations of the wall thicknesses of rough-cut, unpolished, red-hot hollow steel tubes (with 10-micron precision out of 10-millimeter wall thicknesses), moving at speeds

> **Measuring the speed of the vibrating surface is akin to measuring the speed of a crawling infant over a time period of only 100 millionths of a second.**




From N. Toyama, et al., *Applied Sciences* 9:46.

***Lamb waves*, a type of guided wave in a plate, are generated by laser pulse (*at $A_0$*), and can be used to inspect carbon fiber reinforced polymer laminates for damage (*at $S_0$*). An area of damage (*top*) is encountered by a Lamb wave front, which causes a phase delay (*at 40 microseconds*) and reflections (*at 50 microseconds*) that result in the scattering of the incident wave (*bottom*).**

in excess of 4 meters per second along an assembly line, and at temperatures in excess of 1,000 degrees Celsius. The wall thickness is determined by measuring the time it takes for the ultrasound and its echoes to reflect within the thin walls of the tubes.

In a related application, it is important to monitor the strength of a material as it is processed or cast (such as nuclear fuel rods) in a vacuum chamber. Internal granularities and microstructure, which affect the integrity of a material, can be ascertained by measuring the absorption of ultrasound as it reflects between two surfaces of the part and measuring the strength of the echo signals with a probe beam. Highly attenuated echoes are indicative of ultrasound waves that have been extensively scattered by relatively large grain sizes or detrimental microstructure.

In-situ inspection is also important to detect defects in real time during 3D printing, such as one type called *laser sintering*, which uses a high-power laser to solidify material on the top of a powder bed in a zig-zag pattern, after which a new layer of powder is deposited. Cliff J. Lissenden of Pennsylvania State University and his colleagues developed a technique using an ultrasound short-pulsed excitation laser, the output beam of which is formed into a line source that generates ultrasonic surface waves that probe the processed region. A low-power, long-pulsed probe laser beam senses the resultant vibrations on the same or opposite side of the printed area. Spurious reflections or transmission "gaps" are signs of a defect.

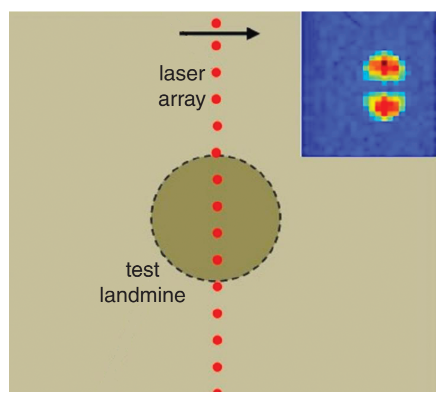
Imaging subsurface impact damage in composite structures is also a critical inspection need. Impact damage is particularly insidious in composites because most often no visible signs appear on the surface. Thus, when a tool is dropped on a composite surface, a mechanic may conclude that no damage occurred, when in fact the impact may have caused extensive subsurface delamination (cracks, fiber breakage, and the like). Laser-based ultrasound has been used by Nobuyuki Toyama and his colleagues at the National Metrology Institute of Japan to detect evidence of impact damage by stimulating ultrasonic waves that are guided along a composite plate, called *Lamb waves,* to interrogate an area in the region of the suspected damage. The Lamb waves propagate along the plate like small water waves, where they are detected by a laser ultrasonic receiver. The presence of impact damage disturbs the Lamb waves just as a stationary rock would interfere with water waves.

## Hidden Patterns

Another application of laser-based ultrasound is in microelectronics. Integrated circuits in semiconductor chips have electrical connections that are made via solder bumps about 500 microns in diameter, and the area around them is filled with epoxy. Intelligent Optical Systems and one of us (Murray) have shown that laser-based ultrasound can be used to perform nondestructive, noncontact testing to determine that all solder bumps are properly bonded. In another demonstration by HRL Laboratories, a laser ultrasound system was used to ensure that there were no epoxy underfill voids or gaps. In much the same way, these systems have been used to detect epoxy voids or debonding in nuclear radiation shielding.

The silicon wafers used in microelectronics can themselves be inspected with a type of laser-based ultrasound called *picosecond metrology*, whereby ultrashort laser pulses (lasting about 100 femtoseconds, or one-tenth of a trillionth of a second) give rise to ultrashort sound waves when absorbed by a semiconductor chip. The sound waves reflect from the chip's thin layers, and a delayed laser probe beam measures these time-dependent changes in reflectivity, thereby revealing the thickness of the chip's thin films down to angstroms in resolution, as pioneered by Humphrey Maris of Brown University.

Recently, Stefan Edwards and his colleagues at the Advanced Research Center for Nanolithography in Amsterdam used this technique to reveal




Courtesy of V. Aranchuk, University of Mississippi

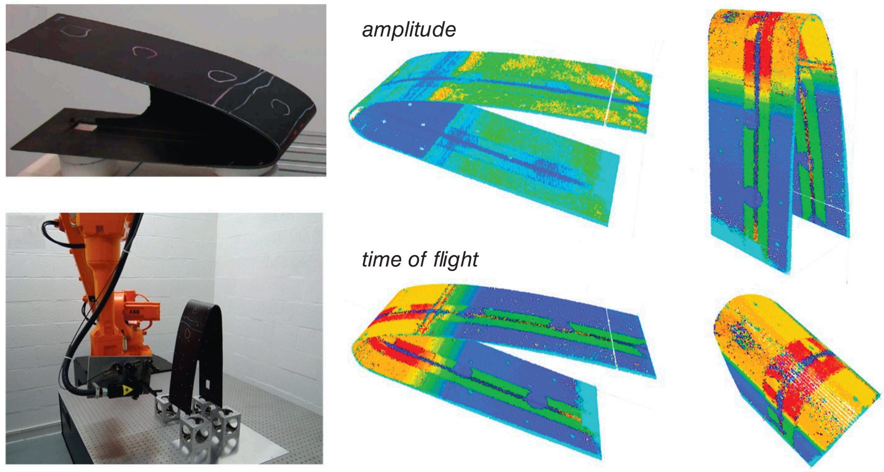
**A buried unarmed test landmine (*circle*) is scanned from a moving vehicle by an array of laser beams (*red dots, moving in direction of arrow*). An audio source induces vibrations that are altered by the buried object, and the vibration pattern difference is detected by the laser system (*inset at top right*). The system has the potential to find plastic landmines, which are difficult to detect with other methods, such as ground-penetrating radar. The noncontact method can be performed at a safe distance.**

hidden patterns beneath opaque thin layers. The hidden structure imprints a pattern onto the sound wave, which diffracts the delayed probe beam. This technique can be useful in the microelectronics industry, in which it is critical to align various buried patterns (such as those that form circuits) with subsequent thin layers of material.

**Under the Surface**

Inspecting below an opaque boundary can at times be dangerous, such as in looking for landmines. The best approach is to use long standoff distances.

In a recent demonstration of landmine detection, performed by Vyacheslav Aranchuk and his colleagues at the University of Mississippi, an array of loudspeakers insonified a distant area in a field. Sound waves penetrated the ground and reflected from underground objects—including unarmed test plastic explosives that ground-penetrating




From J.-F. Vandenrijt, et al., *Proceedings ICEM18* 2(8):455.

**Laser ultrasound can be combined with robotic scanning (*bottom left*) to image composite structures (*top left*) such as ones found in aircraft parts. Irregularly shaped parts can be inspected by a laser beam because the spot where the excitation light is absorbed by the part generates a compressional wave perpendicular to the surface, independent of the angle of incidence. Test flaws marked on the sample are revealed by changes in the amplitude (*top right*) and the time of flight (*bottom right*) of the returned scan signal, shown here in false color.**

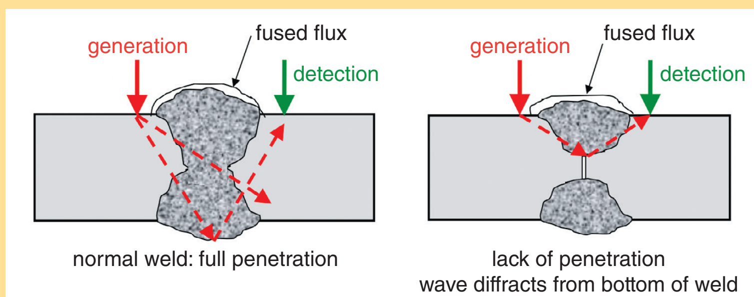
## A Tight Connection

Welding is ubiquitous across most sectors of manufacturing, from microelectronics to the medical sector, the automotive industry, aerospace, and infrastructure. A preferred goal is to inspect weld joints during manufacturing in a nondestructive manner, although in some cases, it is practical to perform the inspection post-processing or offline. Laser-based ultrasound has the capability to perform both in adverse environments.

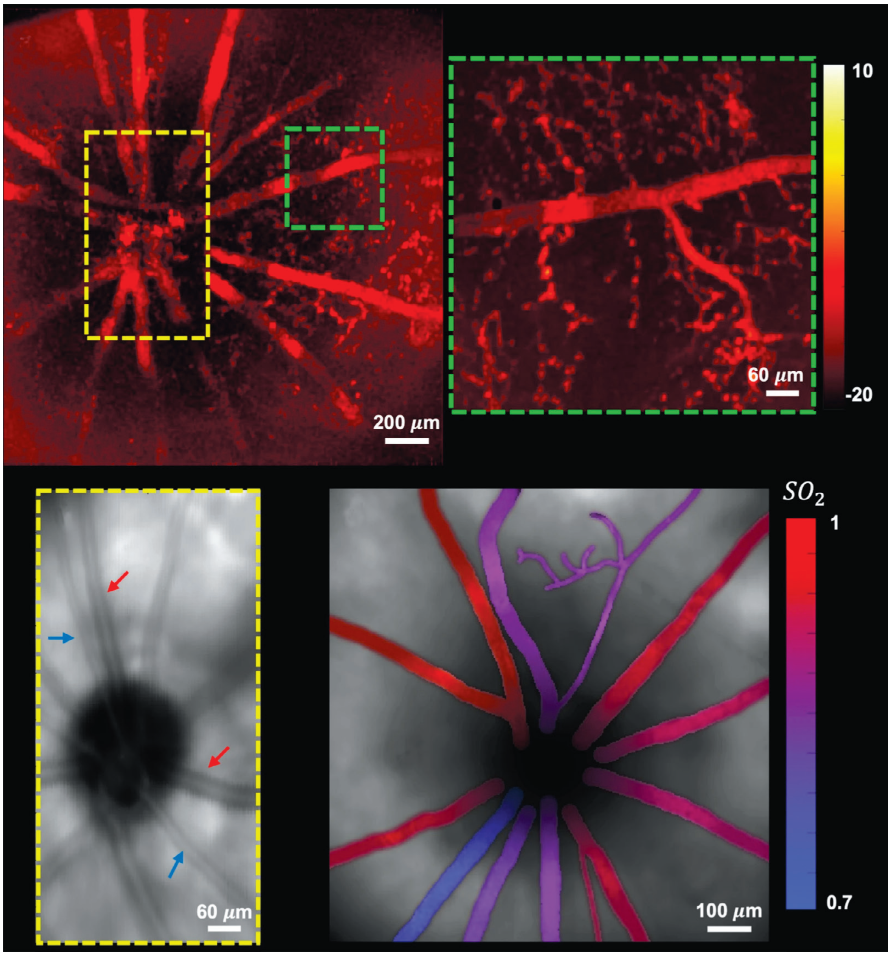
As an example, a weld joint of an automobile automatic transmission reverse clutch housing can be inspected offline, as demonstrated by Gilmore J. Dunning, Phillip V. Mitchell, and one of us (Pepper) at HRL Laboratories in Malibu, California, by “pitching and catching” the laser beams on opposite sides of the workpiece. Two laser beams (the ultrasound exciter and probe beams) were scanned across the weld seam. In the case of a good weld, a high transmission of the ultrasound signal is expected when both beams are on weld-center, and the signal is expected to decrease symmetrically on either side of the weld bead. In current manufacturing, welds are inspected destructively, at random, by sectioning selected workpieces to view the weld bead. The ultimate goal is to implement nondestructive in-line inspection.

In a later demonstration, performed by Marvin B. Klein and Bradley L. Bobbs at Intelligent Optical Systems in Torrance, California, an in-line laser-based ultrasound inspection system was designed and demonstrated to inspect a weld seam during the actual welding process. A good quality weld will not interfere with the passage of the ultrasonic wave; a weld defect will result in spurious reflections of the ultrasound signal in the vicinity of the weld joint, resulting in a decreased signal, or even no signal at all (*see figure below*). Such a diagnostic was installed directly downstream of a laser welder, with the ultrasound generation and probe beams straddling the weld seam, yielding information in real time, with the ultimate goal of providing immediate feedback to the welder system.

A key area of ongoing research is the use of laser ultrasound to perform nondestructive testing of spot welds. The average car contains about 5,000 spot welds. Traditionally, testing is done with intermittent destructive inspection, but obviously not all welds can be inspected in this manner, so the quality of the welds becomes a matter of statistics. In some cases, overwelding is a means of attaining some form of reliability, but it increases production costs. By using pulsed lasers to generate ultrasound on one surface of a metal sheet, the ultrasound wave will travel through the spot-weld unabated, and through the second sheet in the case of a good weld. In the case of a bad weld (either a poor-quality weld bead or a small-diameter weld spot), spurious acoustic reflections will occur that will be detected by the probe laser of the receiver. The optical microphone detection system developed by Wolfgang Rohringer and his colleagues at XARION Laser Acoustics detects laser ultrasonic waves to image spot-welds nondestructively.




Courtesy of Intelligent Optical Systems




From Z. Hosseinaee, et al., *Scientific Reports* 12:4562.

**Photoacoustic remote sensing is used to image the vasculature of a mouse retina (*top left*). Smaller vessels are visible (*top right*) and arteries (*red arrows*) and veins (*blue arrows*) can be distinguished (*bottom left*). The method can measure levels of oxygen saturation (abbreviated $SO_2$) in hemoglobin in retinal blood (*bottom right*). Poor retinal oxygen saturation is indicative of diseases such as diabetic retinopathy and age-related macular degeneration.**

radar cannot easily detect—which created minute surface vibrations. An array of laser beams scanned and probed the surface to detect these vibrations. A challenge here is to collect sufficient laser light from the ground to result in a reasonable signal. Speckle compensation may provide a viable solution.

An exciting application of laser-based ultrasound is in the field of medical imaging. This novel technique involves the detection of subsurface features in tissue, such as blood vessels and tumors, and its name heralds back to Alexander Graham Bell's original discovery. The technique, called *photoacoustic imaging*, employs pulsed or modulated lasers that harmlessly penetrate centimeters into the skin. The modulated light is preferentially temporally absorbed by hemoglobin in the blood. The laser-beam modulation is sufficiently short in duration (lasting tens of microseconds to nanoseconds) that it doesn't just generate heat pulses but also generates ultrasound in hemoglobin-rich features via the thermoelastic effect. These features thus function as subsurface "sources" of ultrasound, as reported in 2016 by Keerthi S. Valluru and Jürgen K. Willmann who were then at Stanford University. A fraction of the ultrasound disturbance propagates to the surface, where minute vibrations occur, as in conventional laser-based ultrasound. By scanning the ultrasound generation and detection beams across the surface of the tissue, a "photoacoustic image" can be obtained, revealing the presence of subsurface blood vessels or tumors against little background. Lihong Wang and his colleagues at the California Institute of Technology have also performed pioneering work in this area.

All-optical imaging approaches such as these may be most suitable for ophthalmology procedures, wound assessment, brain surgery, and laser surgery. For example, in a recent demonstration by Zohreh Hosseinaee and her colleagues at the University of Waterloo, pressure waves modified the reflectivity of a probe beam to realize in-vivo functional and structural retinal imaging using remote photoacoustic microscopy, revealing not only the vasculature of the retina but also its oxygen saturation.

Recently, investigators have explored techniques to further enhance the photoacoustic response of blood. In one case, in vitro experiments were performed by one of us (Murray) and our colleagues using samples of bovine blood, into which were injected 5-micrometer microbubbles, comprising thin spherical membranes housing a molecular species that absorbs light at a much greater rate than blood. Hence, more intense photoacoustic signals would emanate from much smaller volumes than from blood cells within vessels or tumors. The goal is to prepare the surface of these microbubbles with a compound that attaches to, for example, cancerous cells within a blood vessel or tumor, enabling photoacoustic mapping of the cancerous species with high precision.

In another advance, researchers at MIT Lincoln Laboratory and their collaborators at the Massachusetts General Hospital Center for Ultrasound Research and Translation have developed a new medical imaging device: the Noncontact Laser Ultrasound (NCLUS) system. Developed by Robert Haupt and his colleagues, the goal of the technology is to replace conventional, direct-contact ultrasound imaging of patients with the use of noncontact lasers to generate and receive the ultrasound. This advance would enable the imaging of interior body features such as organs, fat, muscle, tendons, and blood vessels—all without touching the patient. The system can also measure bone strength and may have the potential to track disease stages over time. The laser-based system has the potential to diagnose patients who have painful or sensitive body areas, are in fragile states, or are at risk of infection, as well as to image burn or trauma victims, patients with open deep-tissue regions during surgery, premature infants requiring intensive medical care, patients with neck and spine injuries, and contagious individuals, all of whom require long standoff distances.

The system uses a pulsed near-infrared laser—operating safely in the thermoelastic (photoacoustic) mode—to

generate ultrasound waves at a specific location on the patient, not unlike those of a handheld ultrasound transducer, but without contact. A laser Doppler vibrometer, also operating in the near-infrared spectrum and at safe power levels, is used to remotely sense the resultant surface ultrasound vibrations. Both lasers are housed in a robotically articulated arm to precisely locate the pair of laser beams on the surface of the patient. A 2D lidar is used to map the surface topography of the patient's skin; a high–frame-rate, short-wave–infrared camera records the laser source and the projected locations on the skin for the receiver, providing the array parameters necessary for constructing ultrasound images. This noncontact ultrasonic system is in the development stage and promises to be a key diagnostic tool in the medical arena.

**The laser-based system has the potential to diagnose patients who have painful or sensitive body areas, are in fragile states, or are at risk of infection, all of whom require long standoff distances.**

### Maximum Resolution

How small a feature could one "see," or resolve, using laser-based ultrasound? The answer depends on how short a laser "ping" is, a geometrical factor, and the wavelength. As an example, consider aluminum, in which the speed of sound is approximately 6,420 meters per second. For a typical laser pulse of 10 nanoseconds (or 10 billionths of a second), the smallest feature that can be resolved is about 78 microns (a human hair is about 50 microns in diameter). Using an ultrashort pulsed laser with picosecond lengths (trillionths of a second), the smallest feature that can be resolved is about 78 angstroms (an atom is about 3 angstroms in length). Processing techniques that remove speckle can improve this limitation significantly, by factors of five or greater.

To improve laser ultrasound further, on the generation side, more efficient ways of channeling acoustic energy into a preferential band of frequencies, or into a preferential direction of propagation, are being tested. These techniques use multiple light beams that are either properly delayed in time, or strategically distributed along the surface of the specimen, to produce constructive reinforcement (or in other words, focusing) at the desired depth and direction within the sample. This technique is akin to throwing a cluster of small pebbles into a still pond: By carefully tossing the pebbles at specific locations and in a predetermined time sequence, a desired water wave can be generated that can be focused and directed into a given region of the pond. The technique also has been applied in reverse, on the receiving side, by one of us (Murray): Multiple laser ultrasound receiving beams, strategically located on the workpiece, can emulate a synthetic array to detect and analyze the sample with higher resolution sensing of buried flaws and defects at a given location in the workpiece (akin to an imaging microscope).

### Seeing the Future

The use of light and sound to see the interiors of metals, semiconductors, composites, ceramics, and other opaque objects, including human tissue, is no longer just a scientific curiosity but is critical to ensuring the integrity and quality of many manufactured parts and improving medical diagnostics. In the latter case, because light is nonionizing, patients can avoid exposure to potentially harmful x-rays. In the case of airplane components, the safety of passengers can be at stake. Moreover, the safety, lifetime, and performance of satellites, automobiles, nuclear power plants, and the like, which are dependent on the quality and integrity of welds and bonds, can be significantly enhanced through the use of these rapid and contactless inspection techniques. Next-generation factories will need to be equipped with noninvasive sensors to inspect and certify parts remotely without removing them from an assembly line. But as these techniques show, as long as one can see the outside of an opaque object, one can also view and inspect its interior using light and sound.

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# Memories Within Myth

*The stories of oral societies, passed from generation to generation, are also scientific records.*

**Patrick Nunn**

In the 1880s, the American journalist William Gladstone Steel made several visits to a freshwater lake that filled the caldera of an extinct volcano in Oregon. For Steel, these visits were the fulfilment of a dream that began while he was just a schoolboy in Kansas. It was one day in 1870, while reading the newspaper wrapped around his school lunch, that he noticed an article about the "discovery" of a spectacular body of freshwater named Crater Lake. "In all of my life," Steel would later recall, "I never read an article that took the intense hold on me that that one did." When he finally made it to the lake in 1885, he was so captivated that he determined to have the area designated as a national park. But designation was not easily gained and required extensive documentation of the region.

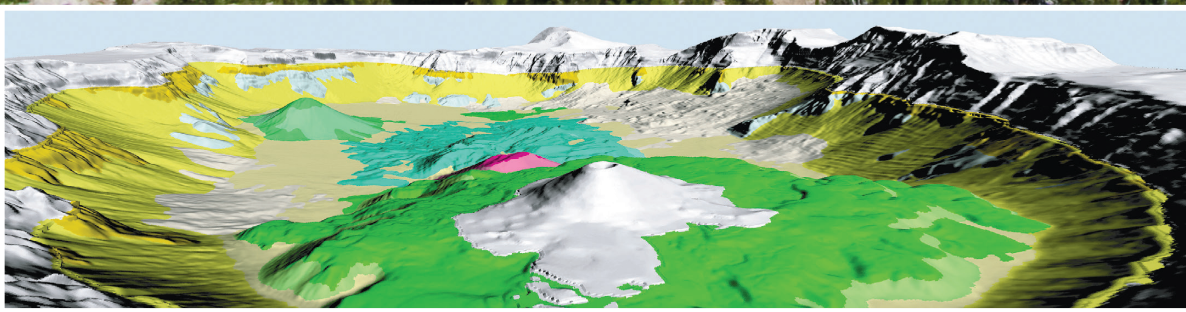
To help with the reconnaissance, Steel engaged guides from the local Klamath peoples, who had occupied the area for countless generations. During their work together, Steel noted that the guides never once looked at the lake itself, instead "making all sorts of mysterious signs and staring directly at the ground"—a sign that the Klamath regarded Crater Lake as a powerful place where a great cataclysm once happened and might happen again. According to Klamath stories, buried deep beneath the lake

**QUICK TAKE**

**The abilities of preliterate** societies to store, organize, and share useful information across generations are often not appreciated by modern literate societies.

**Multiple examples from** around the world demonstrate that oral histories can be thousands of years old, passed down through hundreds of generations.

**The survival of our ancestors' stories** is a testament to humans' capacity to endure through profound, even catastrophic, change, no less important today than millennia ago.



Michael Whyte; USGS

**The eruption and collapse 7,700 years ago of the volcano that formed Crater Lake in Oregon is included in the Klamath peoples' oral traditions. Such oral histories demonstrate the longevity of stories passed down through hundreds of generations. The inset shows the geologic formations above and below the lake's surface today, including Wizard Island (*foreground, in white*) and the Merriam Cone behind it (*green*).**

waters is the spirit of Llao, a demon who lived within the volcano that once towered above Crater Lake. In a past age, Llao terrorized the Klamath by showering them with hot rocks and shaking the ground on which they lived. These attacks continued until Llao was confronted by the benevolent spirit Skell, who pulled the volcano down on the demon and created Crater Lake above.

What sounded to Steel like myth is more than just a story. It is a memory of an eruption that caused a volcano to collapse and form a giant caldera that, as many do, filled with freshwater. The eruption occurred 7,700 years ago, but the Klamath had preserved its story and even sustained associated traditions, such as not looking directly at the lake. Although

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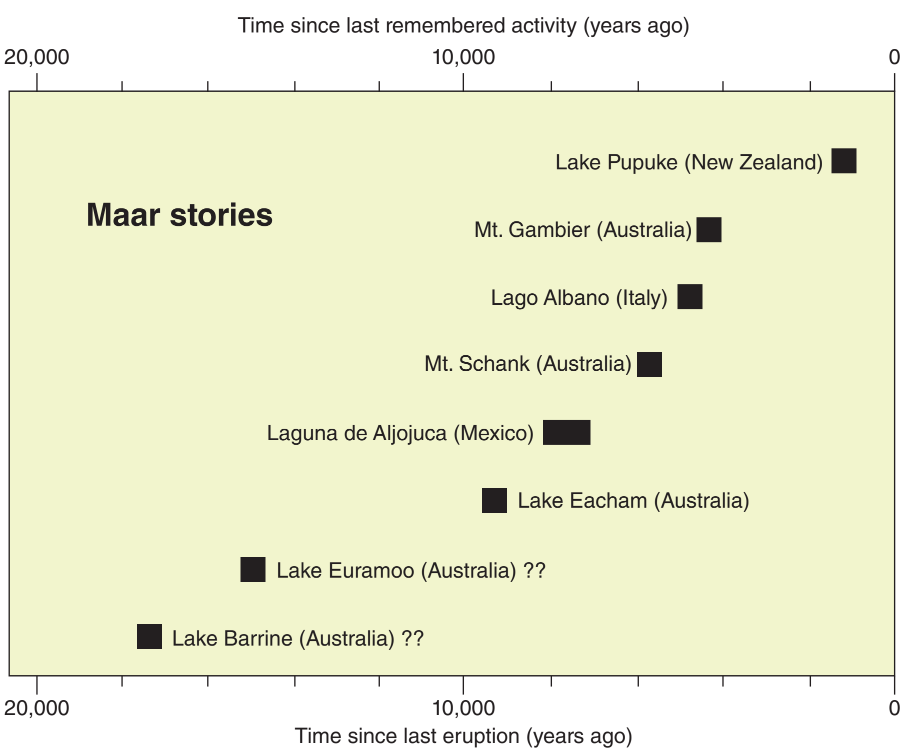



Nunn, et al. 2019.

**Estimated minimum age ranges of formation stories of *maars* (a type of volcanic crater) around the world highlight their remarkable longevity. Some of the best-documented of these stories are from Lago Albano maar in Italy, shown in the above painting from 1800 by Jacob Philipp Hackert. Stories of the Albano maar, which formed at least 8,000 years ago, were first transcribed about 2,000 years ago.**

they did not read nor write when Steel worked with them in the late 19th century, the Klamath people knew a story about an event that had occurred more than seven millennia earlier, a story carried across perhaps 300 generations by word of mouth.

Many literate people today believe this kind of thing is impossible or, at best, an anomaly, because they evaluate the abilities of oral (or "preliterate") societies by the yardsticks of literate ones, where information seems far more readily accessible to anyone who seeks it. In doing so, they undervalue the ability of these oral societies

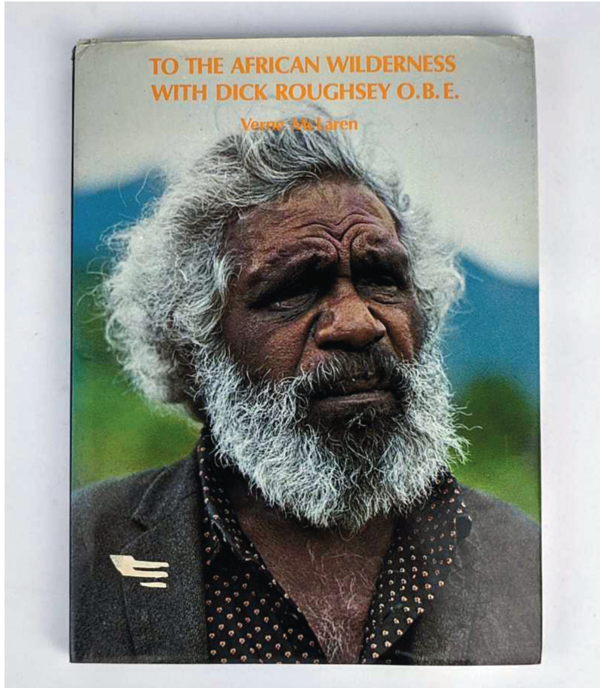
to store, organize, and communicate equivalent amounts of information. In my 2018 book *The Edge of Memory*, I called this misperception "the tyranny of literacy": the idea that literacy encourages its exponents to subordinate the understandings of others who appear less "fortunate." But accounts like Steel's are beginning to help break apart this idea: Oral traditions, rather than being subordinate, are capable of transmitting just as much useful information as the technologies of reading and writing.

**The Longevity of Oral Histories**

In the early 20th century, the French ethnographer Arnold van Gennep spent considerable time familiarizing himself with Indigenous Australian (Aboriginal) oral stories, concluding that these include "fragments of a catechism, a liturgical manual, a history of civilisation, a geography textbook, and to a lesser extent a manual of cosmography." While later research has documented the nature of this information more fully than Gennep realized, especially in the fields of star knowledge and land management, the focus has shifted recently to those types of Aboriginal knowledge for which an extraordinary longevity can be unequivocally demonstrated.

Some of the most compelling examples are of volcanic eruptions that can now be dated with high precision, such as the one that formed Crater Lake in Oregon. These eruptions then become proxies for the age of associated oral traditions. Take the example of the eruption that caused the formation of Australia's maar crater in which Lake Eacham (in northern Queensland) now lies, an event that local Dyirbal-speaking residents described as follows:

> The camping-place began to change, the earth under the camp roaring like thunder. The wind started to blow down, as if a cyclone were coming. The camping-place began to twist and crack. While this was happening there was in the sky a red cloud, of a hue never seen before. The people tried to run from side to side but were swallowed by a crack which opened in the ground. [*Translation by Robert Dixon of Central Queensland University*.]

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**The Lardil storyteller and artist Dick Roughsey (Goobalathaldin) recounted how his ancestors arrived on his home islands, now called the North Wellesleys in Australia, via a peninsula from the mainland. The author's work estimates these islands formed from this peninsula more than 7,000 years ago.**

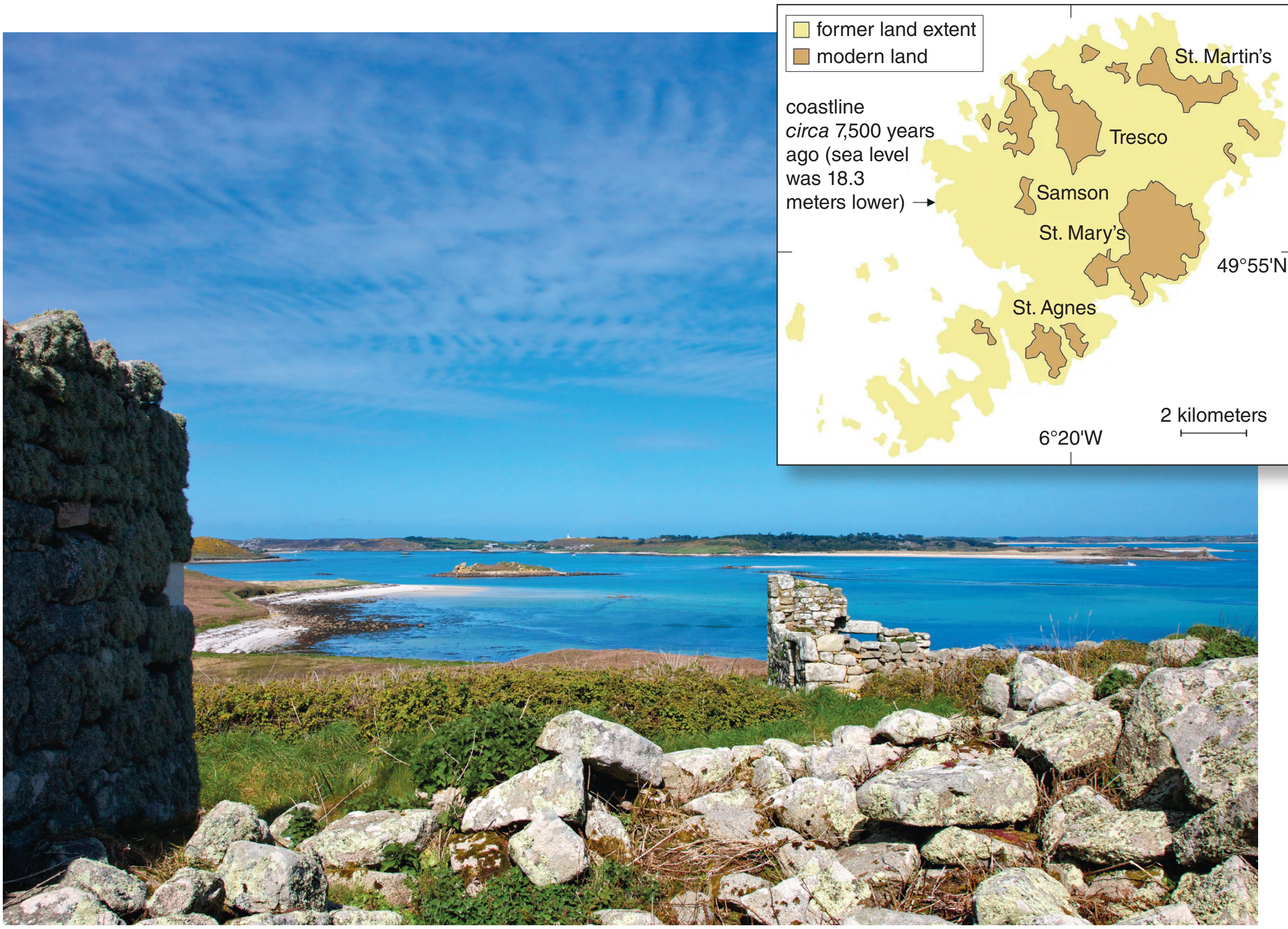
My team's best estimate for the formation of this volcano—and therefore the narrative describing this event—is a little more than 9,000 years ago, as we explain in our 2019 paper in the *Annals of the American Association of Geographers*. A few hours' drive southwest from Lake Eacham brings you to the volcano of Kinrara, estimated by geographer Benjamin J. Cohen of the University of Glasgow and his team to have last erupted around 7,000 years ago. The local Gugu Badhun people have stories about this event, about how the river courses filled with fire—memories of lava flows—and how people were engulfed by "dust" and asphyxiated, details of a kind that retrodictive science is powerless to deduce.

More widespread in Australia are Aboriginal stories of coastal submergence, now known from more than 30 locations all around the continent, that are plausibly interpreted as memories from more than seven millennia ago when the ocean surface was much lower than today, when shorelines were kilometers—sometimes tens of kilometers—further seaward than today, and when today's islands were contiguous with the mainland.

People arrived in Australia around 70,000 years ago, long before the coldest time of the last great ice age when the ocean surface was more than 120 meters lower than it is now, a result of the storage of ocean water within thick ice sheets that once blanketed many continents. When the ice age ended, ice started melting, causing the sea level to rise. This rise continued for 10,000 years or more and caused massive and ongoing disruption to people living in these places. We now know of "submergence stories" from northwest Europe and elsewhere, including Scottish "myths" about postglacial coastal change—but it is the Australian Aboriginal stories that generally contain the greatest detail.

Consider the account of the Lardil storyteller and artist Dick Roughsey (whose tribal name was Goobalathaldin), who explained how "in the beginning, our home islands, now called the North Wellesleys [Gulf of Carpentaria], were not islands at all; but were part of a peninsula running out from the mainland. . . . The Balumbanda

**Ancient myths represent knowledge from times far earlier than those in the world's oldest books.**




Steve Taylor ARPS/Alamy Stock Photo; map courtesy of Patrick Nunn

**The Scilly Isles off the coast of England were inhabited 8,000 years ago when the land was one single island (*inset*). Those people must have told stories about the rapid rise in sea levels that they witnessed, which may have been preserved in Arthurian legends about the lost land of Lyonesse. Today, archaeologists continue to study village ruins and field boundaries there, some submerged or in the intertidal zone, such as this one at Samson Flats.**

[Lardil ancestors] people came along that peninsula long before it was cut up into islands." Geographer Nicholas J. Reid of the University of New England and I estimated that this event occurred more than 7,000 years ago. A remarkable parallel from the other side of the world comes from the Monach Islands in the Outer Hebrides of Scotland. Here, oral traditions collected in the 1860s included stories about times when these islands were connected to the neighboring island of North Uist:

> Owing to the gradual dislodgment of the friable sand forming the isthmus, the isthmus by degrees gave way to fords, and the fords broadened into a strait. . . . Tradition still mentions the names of those who crossed these fords last, and the names of persons drowned in crossing.

The best estimate for the existence of an isthmus connecting the Monach Islands to North Uist is also around 7,000 years ago. So we have solid evidence from two contrasting geographical and cultural contexts of memories recalling land-bridge submergence events seven millennia ago—memories that were, until recently, remembered solely through oral traditions. Though referring to events from millennia ago, these memories were not difficult to recall: In the 1970s and 1980s, Roughsey (Goobalathaldin) filled books with his people's oral traditions; Mary Mackay, the chief informant for the Hebridean stories, was clearly also loquacious, rendering her "vivid" tales in "felicitous Gaelic" according to Alexander Carmichael, the folklorist who collected them during the 1860s.

## The Importance of Collective Memory

These tales of rising oceans are not mere stories. Despite occasional embellishment, their empirical skeletons are easy to recognize. Is it likely that our ancestors across the world sat around inventing stories about times when two landmasses were joined, and insisted on communicating these improbable fictions downstream along the river of history? Or is it more probable that these stories were passed along because people remembered an event so foundational to local history that it was considered hugely important to communicate to each new generation?

Of course, in contexts where there has been considerable mixing of cultures, some of these stories have become mythologized—populated by supernatural beings capable of feats no human could match. Take the example of the giants who feature in myths and legends in every part of the world. Imagine you are trying to tell your ancestral story about how Ireland was once connected to Scotland and Wales, or how Tasmania was formerly contiguous with mainland Australia.

Your audience looks skeptical, so you rationalize your tale, stating that in the old days people were giants, which is how they were able to stride across the expanses of water that people could see. Your audience is satisfied and interest in your story has been recharged, ensuring that it will be retold. But your story has also been transformed, from narrative to myth, meaning it could be regarded as a fanciful or puerile invention dismissed millennia later by literate people as having no value beyond entertainment.

Courtesy Patrick Nunn

**When they met in 2004, Maikeli Rasese told the author the history of Yadua Island in Fiji, including the people who had lived along its coast over the past few generations and a past tidal wave and shipwreck. He demonstrated to the author the sheer breadth of memory necessary to keep these oral histories alive.**

These "myths" are not fiction. Most of the ancient myths of long-established cultures have an empirical core. They are not inventions but observations, filtered through worldviews from potentially thousands of years ago and clothed with layers of narrative embellishment before they reach us today. Framed within the science of their day, they represent knowledge often from times far earlier than those in the world's oldest books.

Victorian-era archaeologist O. G. S. Crawford, an irascible, unconventional, yet hugely influential figure, pondered the veracity of these "myths" with characteristic forthrightness. His focus was on the stories of the "lost land" of Lyonesse off the southwest tip of England. In the inaugural issue of the journal *Antiquity* (which he founded in 1927), Crawford asked whether "the famous legend of Lyonesse . . . had . . . any real basis in fact, or is it merely an invention of the 'dreamy Celt'?" Crawford found "good reasons for believing that the substance of the legend is true," but it is hard to find many people since who have agreed with him. Most commentators conclude Lyonesse to be an "imaginary territory," a place to accommodate historical romance and the birth of nationalist identity—ultimately, it's seen as a lure for tourists. Few scientists dare admit it to the realm of rationalist thought.

Yet the core of the Lyonesse stories is almost certainly true. They plausibly represent the observations of people living on the Scilly Isles 4,000 to 5,000 years ago when the rapid rise of the ocean turned a single large island into a series of smaller islands (*see map on page 364*), much to the alarm, we can infer, of its inhabitants. The land is unlikely to have been called Lyonesse—that name seems to have been introduced during the Arthurian era around the sixth century—but there is robust evidence that the Scillies were inhabited 8,000 years ago when the archipelago was largely a single island. There is also evidence that people witnessed the gradual fragmentation of that island during the following millennia. It is easy to believe those people told stories about what happened, so why is there resistance to believing such stories survived through millennia of oral tradition? The "tyranny of literacy" makes us skeptical of knowledge being retained in oral societies for such a long time. Yet, as awareness of the empirical foundations of "myths" and "legends" grows, such skepticism seems fated to disappear.

**Many literate people undervalue the ability of oral societies to store, organize, and communicate information.**

Many of us assume that people in oral societies were unable to access and utilize the amounts of information that we do. But few literate peoples have considered the implications of this assumption: If people who do not read or write cannot store or utilize the knowledge of their ancestors, then we must conclude that we are here today by luck—luck that would have needed to last around 250,000 years, as long as modern humans have stridden across Earth. You may think my views here are extreme. Stories carried across centuries and millennia are one thing, but can these memories really pass to us from much deeper in time?

### My Oral History Education

Many of the longest-enduring human cultures have ancestral knowledge that in some cases is several hundred years old and has undoubtedly been key to their survival. Countless anthropologists and archaeologists have shown that human societies can retain knowledge for centuries, pointing to the reciting of genealogies as a common example. But survival requires more than lists. It requires people to understand their deep geographical and historical context, their place in the world and how to sustain it. I suggest that our distant ancestors and

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**Oral traditions can only be preserved if people are able to learn them. These stories require comfortable, relaxed environments, such as sitting around a fire at night. Anthropologist Polly Wiessner of the University of Utah has emphasized that group interactions around a fire are foundational to the creation and communication of oral traditions.**

their societies were no less risk-aware or risk-averse than we are today. Their underlying goal was for their bloodline to endure, which is essentially why today we educate young people, teaching them reason, giving them an understanding of the world they inhabit so they might survive. Reason does not depend on books but on acquiring and processing knowledge from whatever sources are available and are best aligned with what we need to know in order to survive.

**I realized I had been privileged to witness the expounding of oral traditions at their best.**

My earliest encounters with people who could neither read nor write (nor, in this case, speak English) were in the Pacific Islands, where I lived and worked for more than two decades. As a geologist, I conducted research in some of the remotest corners of the Pacific region, where my self-belief as a conventional scientist gradually eroded and was replaced with an appreciation of other worldviews equally as valid as that with which I had been inculcated. I also became disabused of the belief—held by most Western-educated literate people—that orality is inferior to literacy. As carefully explained by Walter Ong in his classic 1982 book *Orality and Literacy: The Technologizing of the Word*, not only has literacy transformed human consciousness, shifting it from sound-focused to sight-focused, but it has also "weaken[ed] the mind." As Ong wrote: "Those who use writing will become forgetful, relying on an external resource for what they lack in internal resources." Plato's Socrates noted the same thing, arguing that writing "destroys memory," something that sustained oral societies in every part of the inhabited world for tens of thousands of years.

If there was a pivotal moment in my journey toward an awareness of the depth and breadth of oral knowledges, it was late one afternoon in 2004 when, with some colleagues from the Fiji Museum, I started a conversation with a man named Maikeli Rasese at his home in Denimanu Village, the only settlement on Yadua Island in northern Fiji. We wanted to learn something about the human history of Yadua, of which Rasese was the foremost authority. He described to us each coastal embayment in turn, relating the stories of the people who had occupied it over the past few generations, along with eventful moments in its history, such as a shipwreck, a tidal wave, even the heroic repulsing of invading forces. None of these details were written down. All of it was in his head. And all of it came from his lips in perfect order, fluently, as though he had been reading from a text in front of him.

After a few hours, as we neared the end of our narrative circumnavigation of Yadua—not, by any measure, a large island—I assumed we would shortly conclude our evening. But Rasese was not finished. Having exhausted his historical knowledge of the island, he proceeded to explain where its people had come from originally, how they had abandoned their previous homes on other islands because of growing aggression from new arrivals, and how others of their clan had dispersed but remained in touch, periodically renewing their ties, sometimes through intermarriage, sometimes through the ritualized exchange of traditional valuables. It was 2 a.m. when, seeing his audience drooping with fatigue, Rasese finally ended his storytelling.

The next day, while contemplating the voluminous notes I had made that evening, I realized that I had been privileged to witness the expounding of oral traditions at their best. Such exposition is how it had once been for every group of humans on Earth. Telling these stories was how we optimized our chances of survival, a successful strategy for making sure every new generation was aware of what the previous generation had known.

Under optimal conditions, oral societies were able to pass on knowledge in a coherent form across hundreds of generations to reach us today. We know that oral memories of volcanic eruptions go back more than 7,000 years in several instances; numerous stories of coastal submergence (attributable to postglacial ocean rise) are likely to be of a similar age, some perhaps more than 10,000 years old. The edge of memory is indeed a time horizon of extraordinary antiquity, one that gives us renewed respect for our preliterate ancestors in every part of the world.

Half a century ago, people might remember 10 or 20 telephone numbers, but today how many? Smartphones have almost removed any need to remember phone numbers, birthdays, addresses, or even names. These developments can make life easier, no question, but they also encourage us to undervalue what we have lost.

Humans have a deep-rooted affection for narrative that, I suggest, was born long ago in oral societies. In those times, listening to the stories of your elders was mandatory, not optional. If you didn't listen, you couldn't learn. And if you didn't learn, you wouldn't likely survive. So strong was the communal will to survive that everyone learned—there was no choice. People in oral societies learned to be attentive listeners and, later in life, habitual storytellers.

But good storytellers don't just tell stories. They do whatever they can to engage their listeners, something that applied as much thousands of years ago as it does today. Storytellers perform, they sing and dance, they mimic and entertain. And therein lies the deep roots of what has been ring-fenced in today's literate societies as theater, poetry, dance, and even art. It seems clear that ancient rock art, for instance, had little to do with beauty (although today we often laud its aesthetic qualities) but everything to do with practical wisdom. Such art, it seems, provided memory aids for knowledge-holders, perhaps to populate particularly difficult-to-remember details of important stories. Literate people inherited these things from their preliterate ancestors but repurposed them as cultural creations, not knowing what else to do with them.

**In Community with Ancestors**

Where does that leave us, today? In contemplating the extraordinary longevity of oral traditions, I think it is key to consider the importance of context. It seems obvious to suppose that people learn better when they are relaxed, in an environment where they feel comfortable, where they and their peers are eager to learn. One of the scholarly works that influenced my thinking on this subject was anthropologist Polly Wiessner's insightful research at the University of Utah about the cultural impact of gathering around a fire at night. She suggests that firelight extended group interactions into the night, creating new opportunities for "singing, dancing, religious ceremonies, and enthralling stories" that laid the foundations for the creation and communication of oral traditions. Most of us have felt this phenomenon: There is something primeval about staring into the night-shaded face of a tamed fire, aglow and crackling. It opens a conduit to the past.

Perhaps the greatest lesson we can learn from the nature of ancient stories is that we have been here before, confronting an enduring and profound challenge from climate change that is likely to force major changes to the ways most of us live. But we can take some comfort from the fact that our ancestors survived something comparable: 10,000 years of rising temperatures and sea levels that followed the end of the last great ice age, forcing changes in coastal geographies to which people had no option but to adapt. Our ancestors survived, as did some of their stories, which record their experiences of adaptation as familiar places were submerged and as landmasses broke into islands. We too shall survive, nurturing stories that will one day, thousands of years from now, help *our* descendants survive. That is the way of this world.

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# Beautiful Armor

*The rich variety of mollusk shells reflects the diversity of the phylum, which has fascinated humans for millennia.*

Andreia Salvador

## Fascinating Shells

The beautiful shells pictured here belong to one of the most diverse groups of animals on the planet: mollusks. These invertebrates include snails, oysters, cuttlefish, and chitons, each with their own characteristic type of shell. Most snails have a spirally coiled shell, oysters have a pair of shells called *valves*, cuttlefish have an internal shell, and chitons have an armor-like shell made up of eight separate pieces. And some mollusks, such as slugs, do not have a shell at all.

For those mollusks that have one, their external shell provides protection for the soft body. The shell is made of calcium carbonate and a tough protein called *conchiolin*, which forms the shell matrix into which the calcium carbonate is deposited. Both components are secreted by the mantle, a thin layer of tissue that covers the soft parts of the mollusk's body. As the animal grows, more shell is secreted by the mantle, enlarging the shell.

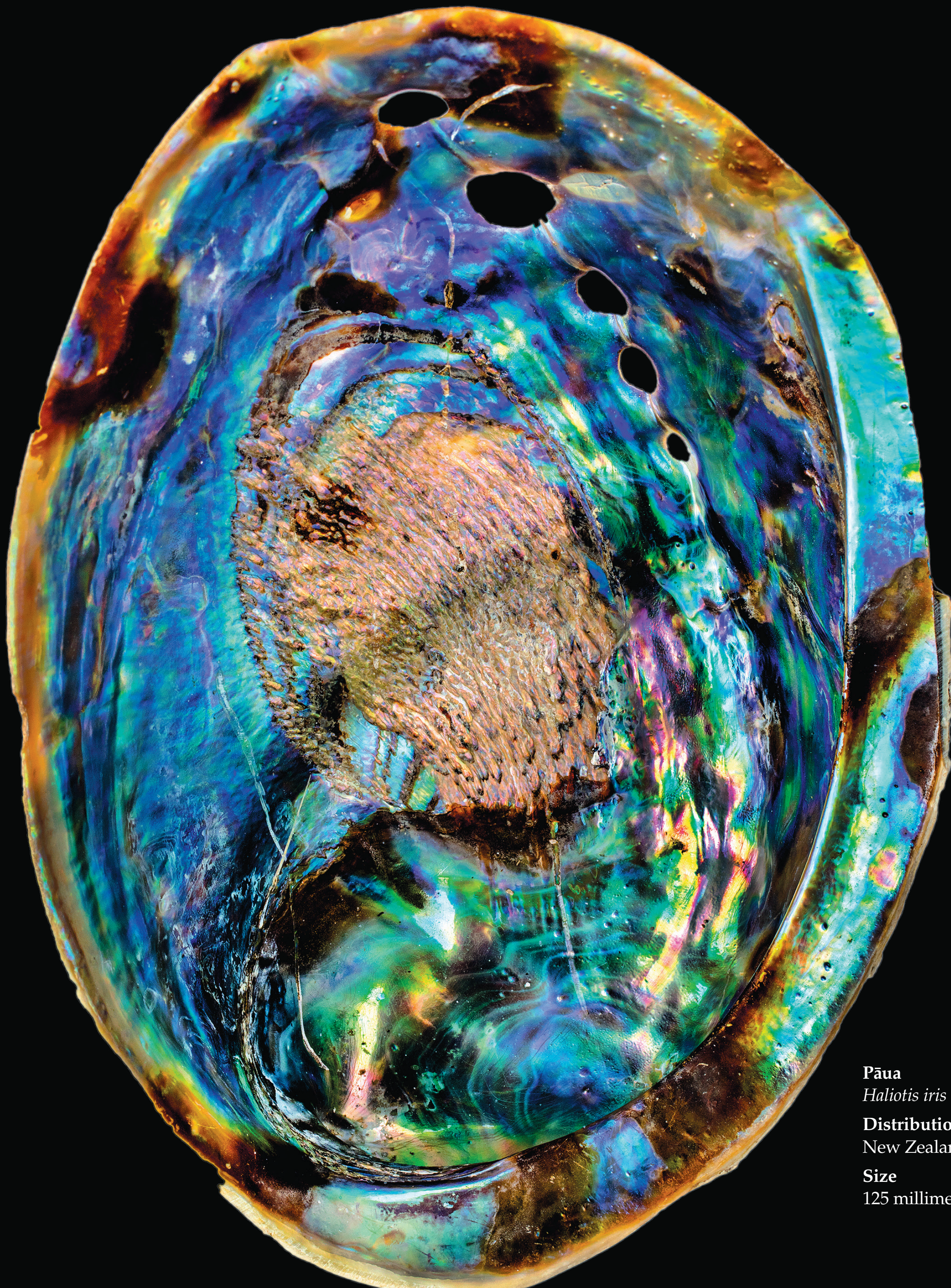
All of the shells featured here come from collections held by the Natural History Museum, London. The size given for each shell refers to its largest dimension (including any spines or other ornaments). The accompanying geographic distribution information gives the known range of the species.

*Andreia Salvador is a senior curator of marine mollusca at the Natural History Museum, London. Photos and text are excerpted and adapted from* Fascinating Shells: An Introduction to 121 of the World's Most Wonderful Mollusks *by Andreia Salvador, published by Natural History Museum, London, and the University of Chicago Press.* *Email: a.salvador@nhm.ac.uk*

**Money cowry**
*Monetaria moneta*
**Distribution**
Indo-Pacific
**Size**
15 millimeters

## Money Cowry

In many parts of the world, until the end of the Roman Empire circa 500 CE, this little shell was used as currency. It continued to be used as small change in the markets of Benin, Ghana, Ivory Coast, and Burkina Faso into the 20th century. Many factors contributed to the shells' success as money, but probably the most significant were that they could not easily be counterfeited (though imitations were produced from bones, ivory, stones, and bronze), they were a convenient and constant size, and they were durable and could be transported easily, like coins. In 18th-century Uganda, one could purchase a cow for 2,500 of these shells, a goat for 500, and a chicken for 25.



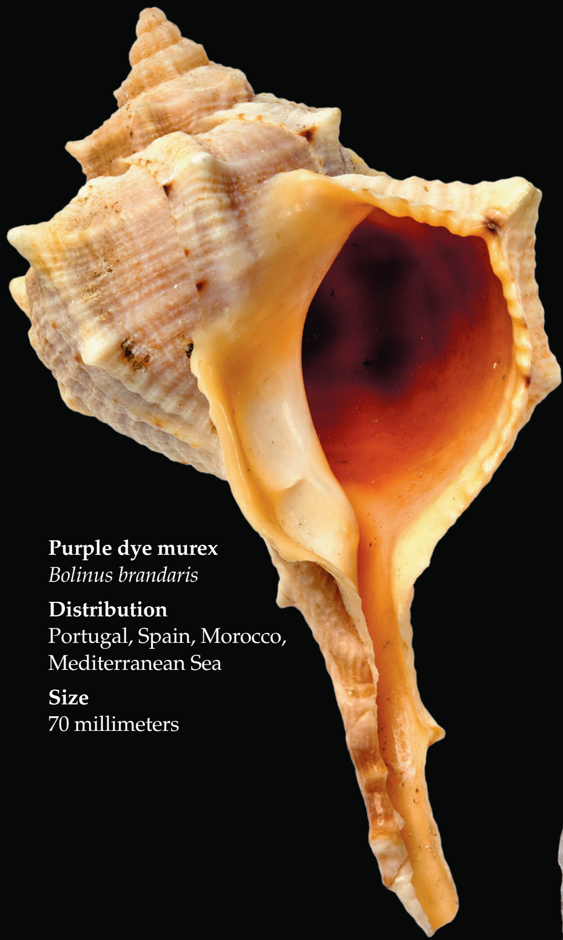
**Pāua**
*Haliotis iris*
**Distribution**
New Zealand
**Size**
125 millimeters

## Pāua

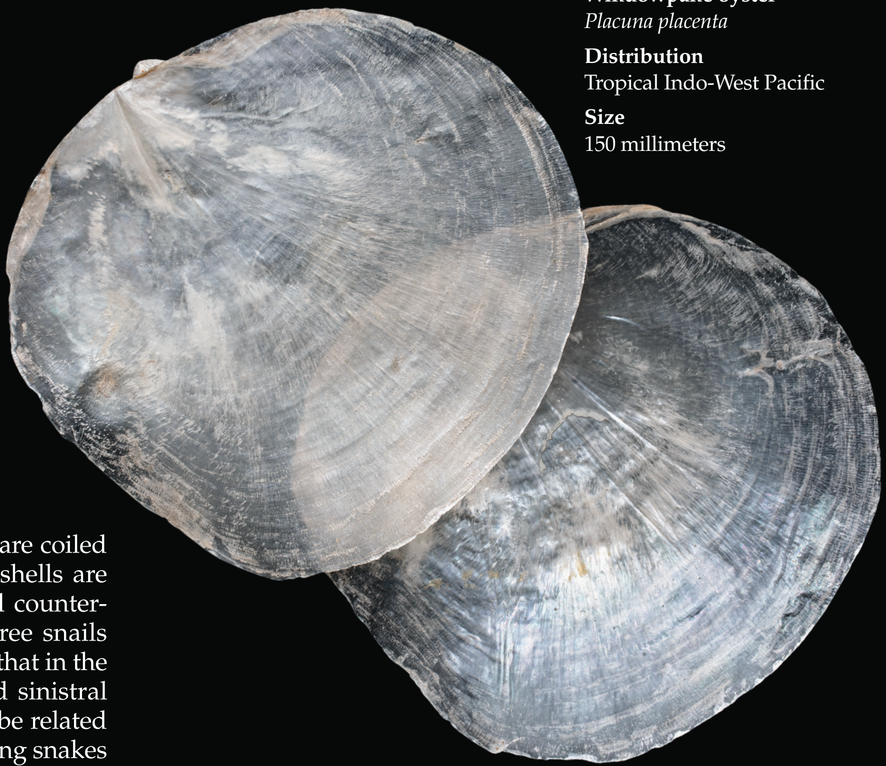
The shell of a mollusk is made almost entirely of calcium carbonate, which the animal extracts from food and seawater. The three layers of the shell are formed simultaneously by the mantle. The outer layer, or *periostracum*, is usually brown or black in color, or is absent in some groups. The second layer, or *ostracum*, is formed of calcite crystals, and the third layer, or *hypostracum*, is formed from aragonite (both calcite and aragonite being different forms of calcium carbonate). In some mollusks, the aragonite crystals cement together in overlapping layers to form mother-of-pearl, or *nacre*. The iridescent colors of nacre are not produced by pigments in the shell but instead are derived from the physical properties of the crystals. Shells that have nacre are polished and carved to make jewelry, buttons, or decorative objects. The pāua, a species of abalone that is only found in New Zealand, is renowned for its blue and green iridescent mother-of-pearl.

## Purple Dye Murex

For thousands of years, people have known how to extract dye from mollusks. The Phoenicians of Tyre in southern Lebanon perfected the process for making a dark reddish-purple dye known as *Tyrian purple*. This long-lasting dye was taken from several species of whelks, including the purple dye murex, *Bolinus brandaris*, and the banded dye murex, *Hexaplex trunculus*, which are found on the Mediterranean and Atlantic coasts. When a murex is disturbed, it retreats into its shell and ejects a fluid, which initially is colorless but, once exposed to sunlight, gradually turns from yellow to green to blue and finally to a purplish red. The dye was expensive—for one gram of dye, more than 10,000 snails were needed. For this reason, the dye was reserved for the garments of individuals of the highest rank. Today, synthetic versions of such pigments are manufactured.



**Purple dye murex**
*Bolinus brandaris*
**Distribution**
Portugal, Spain, Morocco, Mediterranean Sea
**Size**
70 millimeters



**Windowpane oyster**
*Placuna placenta*
**Distribution**
Tropical Indo-West Pacific
**Size**
150 millimeters

## Annam Amphidromus

The direction in which a mollusk shell's whorls are coiled is an important characteristic. The majority of shells are coiled clockwise (*dextral*), but a few species coil counterclockwise (*sinistral*). However, amphidromus tree snails are unusual; they are *chirally dimorphic*, meaning that in the same population one can find both dextral and sinistral individuals. One reason for this variation could be related to their natural predators, snakes. Most snail-eating snakes of the genus *Pareas* have elongated teeth on the right mandible, and for that reason specialize in predation on the dextral shells. These snails have evolved by coiling the other way, which makes it difficult for the snake to grasp and eat them.

**Annam amphidromus**
*Amphidromus inversus*
**Distribution**
Southeast Asia
**Size**
45 millimeters

## Windowpane Oyster

The windowpane oyster is one of the most flattened bivalve mollusks. Its greatly compressed valves hardly leave room for the animal, which lies on the right valve. This oyster is abundant on the muddy bottoms of quiet lagoons, bays, and mangroves in the tropical Indo-West Pacific. It feeds mostly on plankton and organic detritus. Its shell is thin, brittle, and translucent, with a pearlescent appearance, and its outline is nearly circular. This species' common name is derived from its long-standing use in windowpanes in place of glass in various Asian countries. The shells can still be found in the windows of old homes in the Philippines, where they are fished in large numbers and are also manufactured into screens, lampshades, and ornaments.

**Horned helmet**
*Cassis cornuta*
**Distribution**
Red Sea, Indo-Pacific
**Size**
270 millimeters

## Horned Helmet

Coral reefs are one of the richest and most diverse environments on Earth, providing complex and varied marine habitats that support a wide range of organisms. They cover less than 1 percent of the global marine ecosystem, yet they provide a home for 25 percent of all marine species, including thousands of mollusk species. But coral reefs are under threat worldwide. In addition to anthropogenic challenges, one major concern is the crown-of-thorns starfish. These starfish can grow as large as 1 meter in diameter, and they feed on coral. The horned helmet is one of the few species of mollusk that predate on the crown-of-thorns starfish. For this reason, the horned helmet has been put under strict protection in Queensland, Australia, in a bid to prevent the starfish spreading and consuming the Great Barrier Reef.

**Zigzag nerite**
*Vittina waigiensis*
**Distribution**
Southwest Pacific
**Size**
15 millimeters

## Zigzag Nerite

These colorful freshwater snail shells are a wonderful example of the diversity in molluscan shell color, and, although the pattern on each is different, they are all representatives of the same species. Such variable appearance within a species is known as *polymorphism*. The advantage of looking different is possibly very easy to explain: If they all looked the same, predators would only have one pattern to recognize when hunting. With many different patterns, the zigzag nerite confuses predators by making it difficult to establish a consistent search image of their prey.

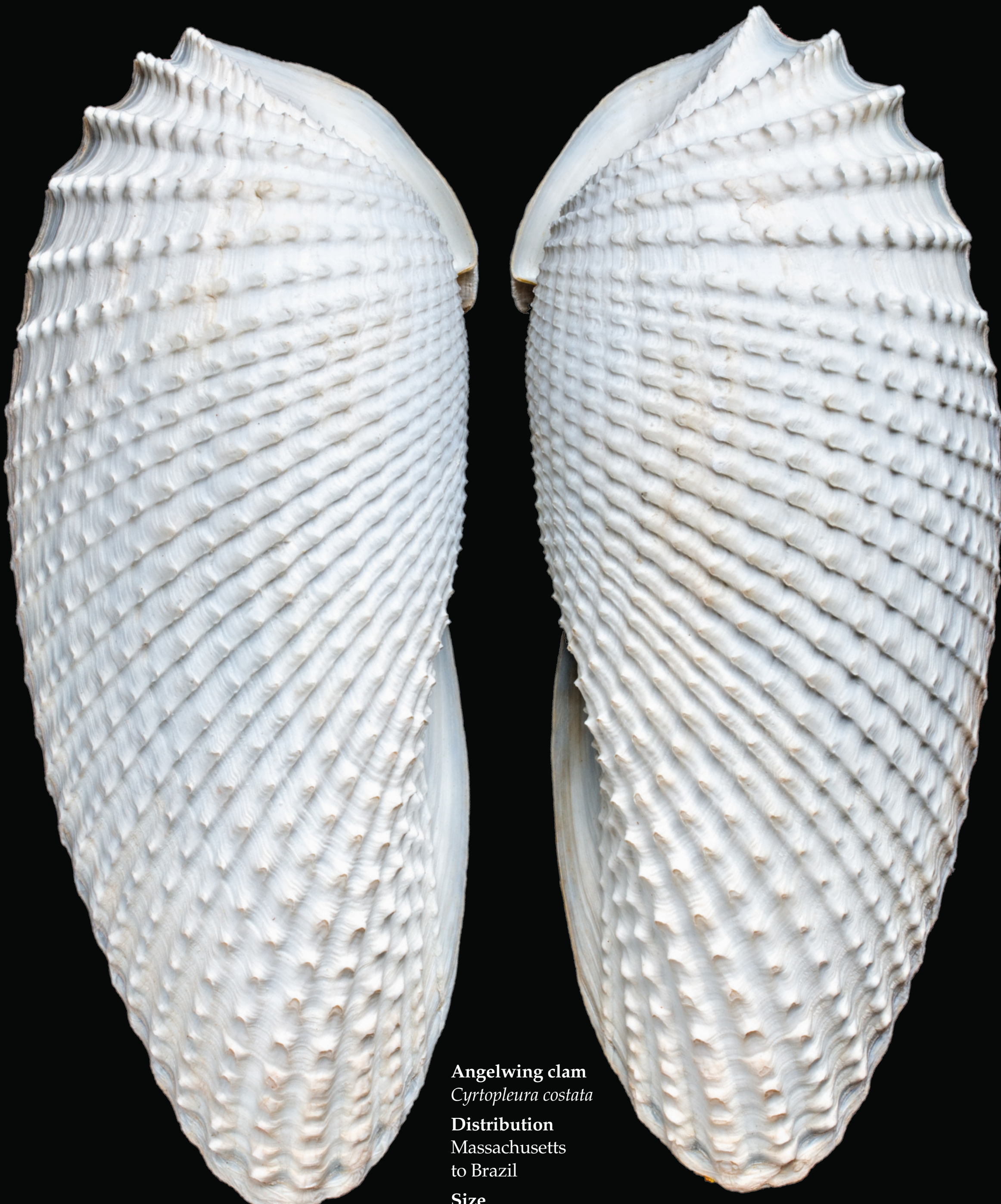
**West Indian worm shell**
*Vermicularia spirata*
**Distribution**
Northwestern Atlantic Ocean, Caribbean Sea, Gulf of Mexico
**Size**
100 millimeters

## West Indian Worm Shell

Most gastropods have regular, neatly coiled shells, but the West Indian worm shell is an exception. Its shell is thin, twisted, and tubelike. The first whorls curl regularly, but as the animal grows, the later whorls become progressively more uncoiled and distorted, so that no two specimens are identical. These marine snails are *sequential hermaphrodites*—they start their adult lives as free-living males, but later change sex and become sessile females, attaching themselves to various substrates such as sponges or other colonial animals.

## Angelwing Clam

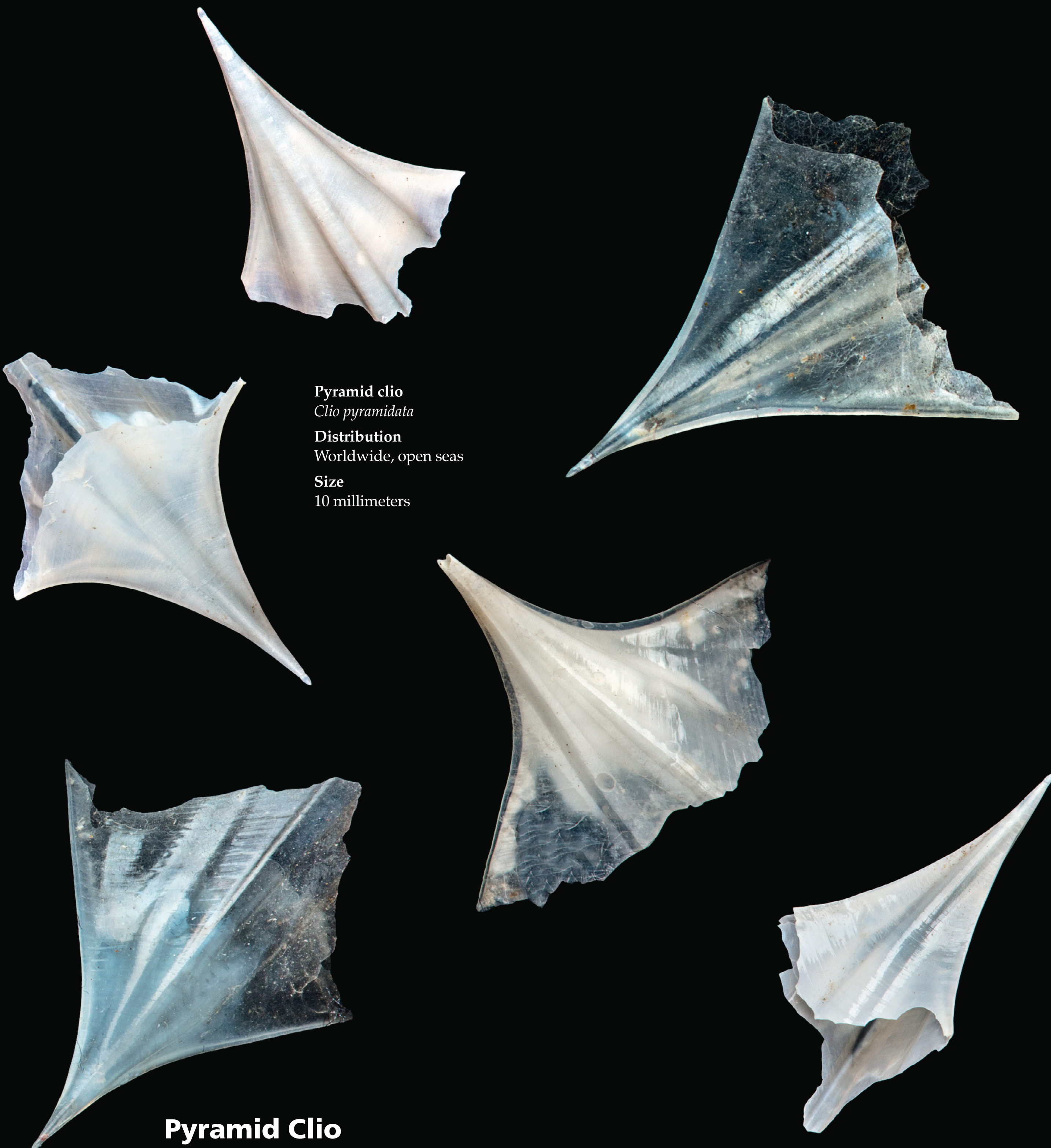
Many marine mollusks burrow into the sand or mud of the seabed to hide from predators. Others, like all members of this family of bivalves, the *piddocks*, are borers. They excavate permanent tunnels in mud, clay, limestone, wood, or even rock. They bore by a slow twisting movement of the valves, controlled by their muscular foot. The thin and usually elongate shell has a very rough surface on the front end that rasps into the substrate. Angelwing clams have strikingly beautifully white shells. They live in shallow, subtidal waters, boring in soft mud to depths of up to 1 meter. They are suspension feeders, feeding solely on plankton, and are usually found in scattered colonies of several dozen individuals.



**Angelwing clam**
*Cyrtopleura costata*

**Distribution**
Massachusetts
to Brazil

**Size**
120 millimeters



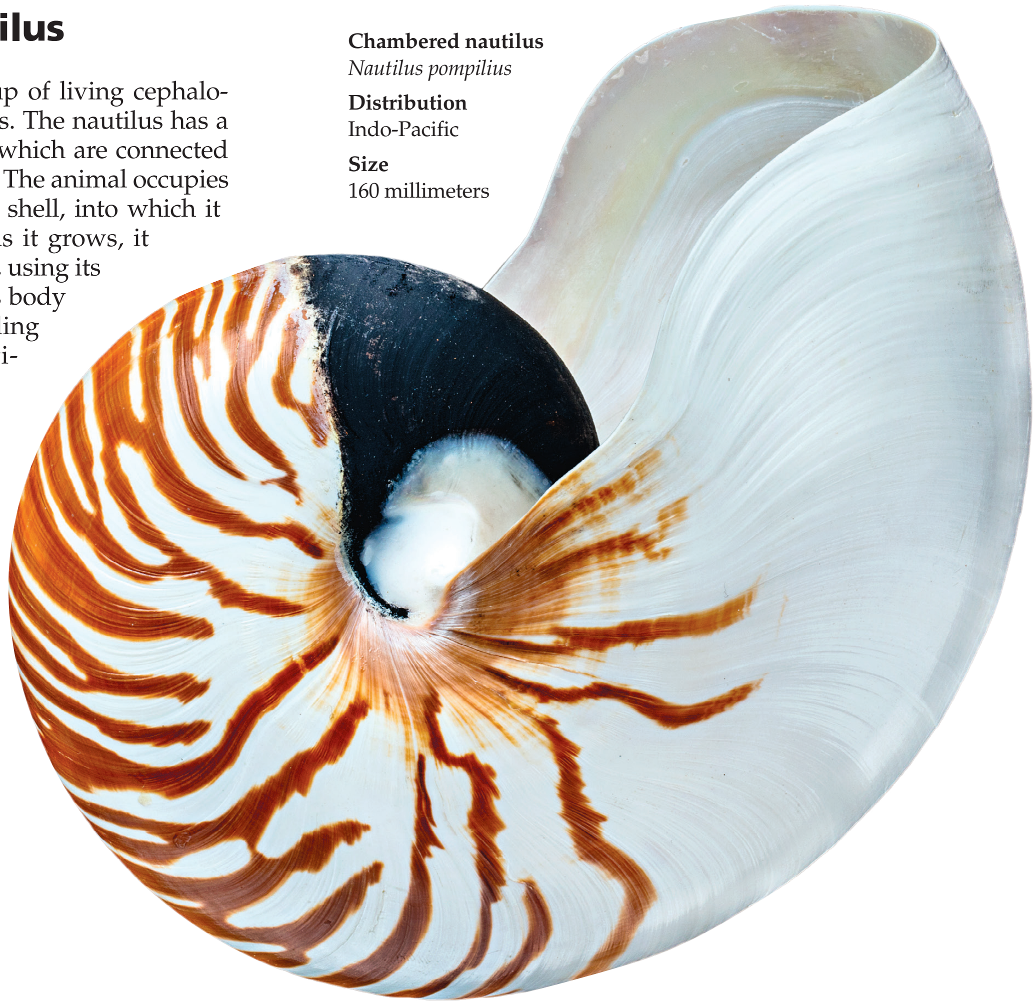
**Pyramid clio**
*Clio pyramidata*
**Distribution**
Worldwide, open seas
**Size**
10 millimeters

## Pyramid Clio

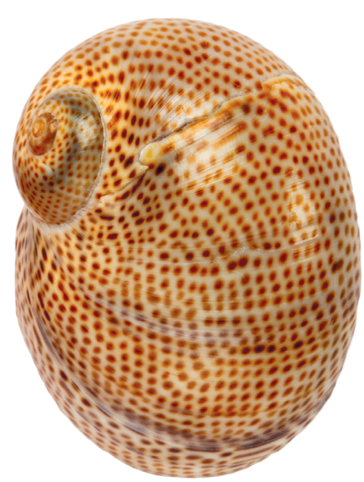
This small, fragile, and translucent shell belongs to a group of pelagic gastropods called *pteropods*. The world's oceans are heavily populated with these small snails, which form part of the plankton. Pyramid clio provide a vital source of food for many small and large aquatic organisms. They are also named sea butterflies because the animal has two large, winglike extensions on its foot, which can be flapped like the wings of a butterfly. Because their shells are exceptionally vulnerable to rising levels of carbon dioxide, these organisms have been proposed as bioindicators to monitor the effects of ocean acidification. Acidification occurs when oceanic waters absorb the atmospheric carbon dioxide released mainly from the burning of fossil fuels. At a certain threshold, the acidity dissolves the snails' shells, and they, like many other mollusk species, cannot survive without their shell to protect them.

## Chambered Nautilus

Nautiloids are the only group of living cephalopods with true external shells. The nautilus has a shell made up of chambers, which are connected by a tube called the *siphuncle*. The animal occupies only the last chamber of the shell, into which it can withdraw completely. As it grows, it creates a new larger chamber, using its 90 or so tentacles to move its body into the new space and sealing off the vacated one. Nautilus shells had been carved, etched, and engraved for many centuries. They rose to prominence in Europe during the 17th century when European craftsmanship reached new heights, particularly in the Netherlands. The carved shells were popular items in cabinets of curiosities and were among the most coveted natural history objects.



**Chambered nautilus**
*Nautilus pompilius*
**Distribution**
Indo-Pacific
**Size**
160 millimeters



**Fly-specked moon snail**
*Naticarius stercusmuscarum*
**Distribution**
Mediterranean,
Northwest Africa
**Size**
30 millimeters

## Fly-Specked Moon Snail

Moon snails, or necklace shells, belong to a large family comprising several hundred species distributed throughout the world. They are an extremely diverse group that spans all marine habitats, from pole to pole, from the intertidal to the abyssal depths. These gastropods are active predators, feeding mostly on bivalves that live below the surface of the sand. After enveloping their prey with their disproportionately large foot, the snails drill a very neat circular hole through their victim's shell in order to eat the animal inside. They use their radula to drill the hole and scrape away shell material, which is softened by a chemical secreted by an accessory organ. This method does not work every time, so the shells of prey species may be found with unsuccessful drill holes.

# Scientists' Nightstand

*The* Scientists' Nightstand, American Scientist's *books section, offers reviews, review essays, brief excerpts, and more. For additional books coverage, please see our* Science Culture *blog channel online, which explores how science intersects with other areas of knowledge, entertainment, and society.*

**ALSO IN THIS ISSUE**

**PERIPHERY: How Your Nervous System Predicts and Protects Against Disease.** By Moses V. Chao.
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**ONLINE**

**On our *Science Culture* blog:**
*www.americanscientist.org/blogs/science-culture*

**Trailblazing Women Botanists in the Grand Canyon**

Book review editor Jaime Herndon reviews Melissa L. Sevigny's *Brave the Wild River: The Untold Story of Two Women Who Mapped the Botany of the Grand Canyon*.

**From *Brave the Wild River: The Untold Story of Two Women Who Mapped the Botany of the Grand Canyon.***

## A Quantum History of Space-Time

Chanda Prescod-Weinstein

**ON THE ORIGIN OF TIME: Stephen Hawking's Final Theory.** Thomas Hertog. 352 pp. Bantam, 2023. $28.99.

Last year, I had the opportunity to give a TED Talk on the main stage. A few days before the event, I had dinner with other people who would also be giving talks about science. As we settled in, a nuclear energy influencer (that's a thing, I learned) asked me what I did. I explained that I'm a theoretical particle cosmologist, who mostly tries to understand what dark matter is. She looked at me with sincere confusion and asked, "How is that useful?" With *On the Origin of Time: Stephen Hawking's Final Theory*, Belgian physicist Thomas Hertog offers a passionate rebuttal to those who think the only science that matters is that which has obvious and near-term material value.

The answer to that influencer's question? As Hertog writes, "Stephen's final theory offers a powerful kernel of hope." Braiding together the history of cosmology and the story of his working partnership with Hawking, Hertog contributes to the extensive literature for general audiences on the origins of the universe by offering, at heart, an homage to a beloved mentor. Hertog completed his doctoral work under the supervision of Hawking, which is explored in *On the Origin of Time*, and this led to an enduring research partnership that was still productive until nearly the end of Hawking's life.

The "final theory" mentioned in the book's title addresses the questions that Hawking spent his entire career chasing: How did space-time begin, and what is a correct narrative of its evolution? Ultimately Hawking, in collaboration with Hertog and other scientists, came to the conclusion that in order to understand the past, we must begin with the present and understand that quantum mechanics means there is no such thing as a classical, linear past unfolding behind us. This top-down approach, as Hertog terms it, is antithetical to our typically taught and learned understanding about time.

But for physicists, especially cosmologists, this perspective is nothing new. Our early training as relativists involves reconfiguring our conception of time as both relative and, under many circumstances of interest, mixing with space, to form space-time. Our training in quantum theory also teaches us that even the simplest physical systems do not necessarily have a deterministic evolution like the one that Newtonian physics promises us. In other words, we can calculate probabilities about the final state of a system, but we cannot guarantee it. What happens when you apply this idea to the whole universe at once? Hertog claims that, necessarily, one must land at a theory of quantum cosmology that he calls Hawking's final theory. This means that we must let go of fixed notions of history where there is only one pathway to the past. In other words, we must shift away from deterministic notions of physical history.

In trying to summarize the top-down model for this review, I faced a challenge that Hertog also had to confront head-on in his more than 300-page text. A decent amount of background material is necessary in order to fully appreciate the ideas from which Hertog and Hawking drew to develop their no-boundary model of how the universe began. For exam-

ple, readers must understand that if we run our cosmological models—as described by Einstein's gravitational equation—in reverse, we land at a mathematical singularity at time equal to zero. The jury is still out on whether this is a physical singularity—a phenomenon where space-time is no longer well-defined. At base, this is the problem that Hawking (who was also responsible for identifying it) spent the rest of his career investigating.

We are not hopeless in this pursuit: The space-time singularities that arise in what we term classical cosmology potentially go away, or at least shift in nature, when we bring quantum mechanics into the picture. Hertog chooses to narrate these scientific questions largely through the frame of history, first by giving a chronological narrative of classical cosmology, then offering an introduction to how quantum gravity string theory provides fresh insights, before finally returning to the fundamental ways in which basic ideas and results from quantum mechanics encourage us to rethink absolutely everything.

Before arriving at these historically infused (and almost exclusively men-only) introductions to the quantum and cosmological questions at hand, Hertog offers an extensive chapter on how Darwinian evolutionary theory reconfigured biology, providing insights from which Hertog and Hawking would later borrow. In my view, that promise is unfulfilled before the book is over, but it wasn't overly bothersome to me. The question of how to interpret the history of our cosmos without the guarantee of determinism is a fundamentally profound question that will bother physicists in the best possible way, but will also be interesting and exciting to any curious person who has the right conditions to sit and wonder.

Due to the way the book is set up and the order in which Hertog presents events and ideas, we don't get to the cool ideas soon enough. The early excursion into evolution and biology could have been cut short, if not entirely. When I've asked colleagues about the ideas that Hertog advances at the very end of the book, some of them feel that the final theory is more vibes than substance, but I'm alright with that. I wish I had spent more of the book knowing what vibes we were going to land in, with a stronger sense of where


Photo credit: Thomas Hertog and Jonathan Woods.

**Thomas Hertog and Stephen Hawking worked together for nearly 20 years, exploring a new theory of physics and cosmology. After Hawking lost the ability to use his clicker, the two had a system of nonspeaking communication that included facial expressions.**

Hertog was leading the reader. In addition, Hawking's genius and reputation are so imposing on the text that Hertog himself disappears, to a certain extent. I find that unfortunate, because he is an accomplished scientist in his own right who has coauthored nearly 100 scientific papers—mostly with people who are *not* Stephen Hawking—on a range of topics that tackle major questions in theoretical cosmology.

Overall the book is hagiographic in nature, but I struggle to impugn this. I also have scientific mentors, at least one of whom is mentioned in this book, about whom I would write only the most glowing words. While I could have done without Hertog's historical approach to narrating scientific ideas, *On the Origin of Time* works hard to capture some of the awe-inspiring spirit of Hawking's *A Brief History of Time*, complete with extensive explanations and helpful figures. At the age of 10, I chose theoretical cosmology because I saw a documentary based on that bestseller; this book might do the same for someone else.

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*Chanda Prescod-Weinstein is an associate professor of physics at University of New Hampshire and author of* The Disordered Cosmos: A Journey into Dark Matter, Spacetime, and Dreams Deferred *(Bold Type Books, 2021).*

# To Fix the Brain, Look to Other Nerves

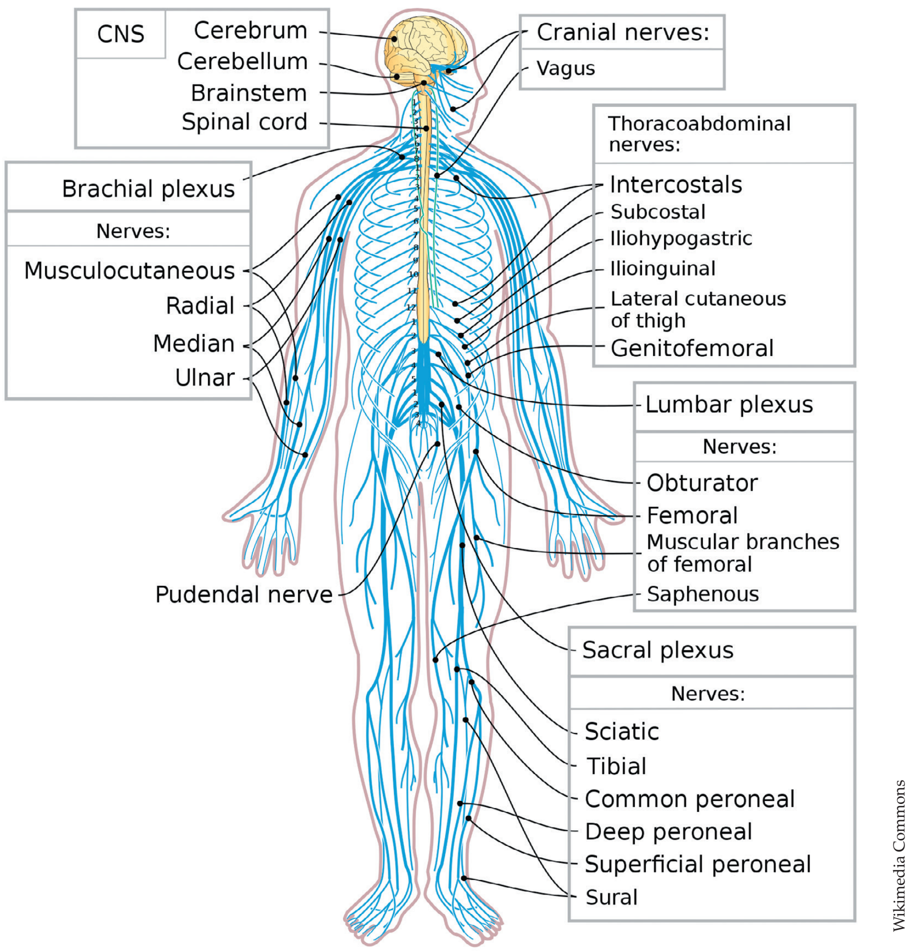
Sara Manning Peskin

**PERIPHERY: How Your Nervous System Predicts and Protects Against Disease.** Moses V. Chao. 192 pp. Harvard University Press, 2023. $29.95.

In 2015, thousands of researchers descended on a Chicago convention center for a gathering of the Society for Neuroscience. On the event's second-to-last afternoon, Francis Collins, then-director of the National Institutes of Health, rose to the podium amid a standing-room-only audience. The brochure promised a lecture about brain research.

By the time the talk ended, though, Collins was advocating for his listeners to explore something entirely different than what had been billed. The community of neuroscientists, he argued, should train its eye on the many neurons and networks that sit outside the brain and spinal cord. There, in the peripheral nervous system, lay some of the body's most important, undiscovered clues to certain illnesses.

Moses V. Chao, a professor at New York University and a former president of the Society for Neuroscience, was in the audience that day. In his debut book, *Periphery: How Your Nervous System Predicts and Protects against Disease*, Chao heeds the call from the Chicago convention. His book is a celebration of the peripheral nervous system, a 192-page biography of an underappreciated, overshadowed body part.




**The peripheral nervous system relays messages between the brain and the spinal cord to the rest of the body. Because it doesn't have the protections that the brain and spinal cord have, such as the skull or vertebral column and the blood-brain barrier, the potential for exposure to various toxins is increased.**

**In the midst of peripheral nervous system dysfunction, we just might find a cure for diseases that, on the surface, appear to simply be problems of the brain.**

The peripheral nervous system includes all nerves outside the brain and spinal cord. This definition is misleading in its simplicity; in part because those nerves take on such varied assignments. They carry sensory information *to* the brain, convey motor commands *from* the brain, and direct the automated functions of the heart, gut, and other organ systems.

In *Periphery*, Chao argues that these nerves are under-recognized sensors and controllers of human health and disease. To make his case, he begins by explaining how the peripheral nervous system evolved long before the brain, in a tiny worm that roamed the deepest seas 600 million years ago. After touching on the gut-brain connection and the role of pain-sensing neurons, the bulk of Chao's discussion focuses on the peripheral nervous system's possible role in Parkinson's disease and three other diseases.

Although we think of Parkinson's disease as being a problem in the brain—particularly in the deep cerebral regions that modulate movement—Chao writes convincingly that the condition may actually begin in the nerves of the gut. One of the earliest symptoms of Parkinson's disease is constipation, which often starts years before the stereotypical trembling and stiffness. Lewy bodies, the microscopic hallmark of

Parkinson's disease in the brain, can also be found dotting the nerves that run along the gastrointestinal tract. Patients who have undergone an appendectomy are less likely to develop Parkinson's disease, suggesting that the vestigial appendage may be an early pathologic hideout. The vagus nerve even serves as a likely suspect when it comes to explaining how a brain disease could start outside the head. This beefy structure, which runs from the abdomen into the skull, may serve as an anatomical highway for pathologic proteins to make their way from gut to brain.

Chao eventually asserts that the peripheral nervous system has been taken for granted because its work is done subconsciously. When we pet a dog, we don't have to tell the cells in our fingertips to communicate the feeling of fluffiness to our brain. But when these processes go awry, producing chronic pain or opening the gates for neurodegeneration, we should pay attention. Chao claims that, in the midst of peripheral nervous system dysfunction, we just might find a cure for diseases that, on the surface, appear to simply be problems of the brain.

*Periphery* moves at a rapid clip, touching on many topics, perhaps at the expense of extended discussion, but it still stops along the way for brief portraits of some of the greatest researchers in the history of neuroscience. Jean-Martin Charcot coined names for at least 12 neurologic disorders, including multiple sclerosis, Tourette syndrome, and amyotrophic lateral sclerosis (ALS). A talented sketch artist, Charcot discerned disease patterns by seeing commonalities in his patients' postures and expressions. Rita Levi-Montalcini, another scientist portrayed in the book, conducted research in a bare-bones laboratory in her bedroom during World War II, when she was prohibited from working in Italian universities because she was Jewish. She went on to win a Nobel Prize for discovering a protein that helps nerves grow. Although the subtitle of *Periphery* makes clear that science is the main focus, rather than the scientists, the recurring cast of characters enriches the text and conveys how interconnected the world of neuroscience really is.

Chao's book is a sweeping tour that caters primarily to those with a

## The Power of Data Literacy

Back-to-school season is well underway, and with the recent focus on increasing students' ability to utilize evidence-based decision-making, one core curriculum standard that is emphasized by high school teachers is data literacy. That's a key theme in the graphic novel *Power On!* written by Jean J. Ryoo and Jane Margolis and illustrated by Charis JB.

What happens when a supposedly objective AI system is actually racially biased, and causes real harm in the community? Can an algorithm be racist? That's what a diverse group of friends decides to find out in this timely story. Growing up around tech, they've always felt pretty tech-savvy—but after the AI incident, suddenly they're not so sure. The friends decide they want to learn more about computers by taking some computer science classes at their various high schools, but with mixed results. Although some of the friends have teachers who


Excerpted from *Power On!* By Jean J. Ryoo and Jane Margolis. Reprinted with permission from The MIT Press. Copyright 2023.

discuss issues of equity in technology and take them on field trips to local companies, others have instructors who only teach typing and basic website setup. Some of the kids are even shut out of classes entirely and told they'd be "better off" learning other subjects. After-school computing clubs fill in some of those gaps, teaching the students about programming wearable tech.

In the excerpt shown here, the friends have determined they need to take a more active role in accessing computer science education. They have taken a teacher's suggestion to present at their local school board meeting, and in order to prepare, they have decided to call all the schools in their district to see which even offer computer science. The students need to effectively present their data, as well as support their point with statistics about the demographics of students who enroll in these classes. Ryoo and Margolis hope that this story will inspire students to investigate their own districts' offerings, and encourage them to take an active role in increasing access to classes. Teachers could take this story and create a project in which students decide on a local problem about which they have to gather, analyze, and present data.

Ryoo and Margolis have created a fun and engaging story that explores the importance of computing and data education, biases in education, issues in equity and ethics in tech, and much more. Braiding together the stories of these friends with explainers on computer science and profiles of people of color and women in tech, this book is highly informative for young people wanting an accessible intro to computer science and tech. *—Fenella Saunders*

background in neuroscience. The text moves quickly from one topic to the next, often delving into arcane medical details, so lay readers may find themselves adrift amid the terminology and the nonlinear narrative. Nevertheless, Chao proves to be a capable guide, and at many points it feels as if he is a personal mentor sitting at the front of a small classroom, expounding on his years of experience.

The final note in *Periphery* feels almost futuristic. Efforts to induce neurons in the brain to regenerate have proven slow-moving despite significant funding, in part because these nerves produce proteins that impede regrowth. For the solution, Chao proposes we look to the peripheral nervous system, where damaged neurons regrow successfully all the time. "The periphery holds the answers for regeneration," he states passionately, adding later that he sees the peripheral nervous system as the key to extending lifespan. Let's hope he's right.

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*Sara Manning Peskin is an assistant professor of clinical neurology at the University of Pennsylvania. She is the author of* A Molecule Away From Madness: Tales of the Hijacked Brain *(W.W. Norton & Co, 2022), a* New York Times *Editors' Choice.*

Sigma Xi Today
A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

## Sigma Xi Elections Begin November 13

Active Sigma Xi members will receive a ballot from **elections@vote-now.com** to begin voting in the 2023 Sigma Xi elections. All members who receive a ballot can vote for the president-elect, as well as for other open positions in their chapter's region and constituency. Members who aren't affiliated with a chapter can vote for candidates in the Membership-at-Large Constituency Group. Ballots will be personalized with the candidates who pertain to each member.

**President-Elect** — Three-year term beginning July 1, 2024: the first year as president-elect, the second year as president, and the third year as immediate past president.

**Directors** — Three-year term beginning July 1, 2024. Director positions up for election serve the Baccalaureate Colleges Constituency Group, Canadian/International Constituency Group, Northwest Region, and Southeast Region.

**Associate Directors** — Three-year term beginning July 1, 2024. Associate director positions up for election serve the Membership-at-Large Constituency Group, Research & Doctoral Universities Constituency Group, North Central Region, and Southwest Region.

**Representatives on the Committee on Nominations** — Three-year term beginning immediately after the election. Representative positions up for election serve the Comprehensive Colleges & Universities Constituency Group; Mid-Atlantic Region; Northeast Region; and Area Groups, Industries, State & Federal Labs.

Visit **sigmaxi.org** to learn more about the 2023 election candidates and position responsibilities.

Sigma Xi Today is managed by Jason Papagan and designed by Chao Hui Tu.

## From the President

### Of Mice and Mental Health

In the world of mice, with whom humans share a common ancestor according to one theory of evolution, an interesting experiment was performed more than 15 years ago. In the experiment, a mouse is confronted with two paths: one leading directly to chocolate, the other leading to a second mouse whose access to the chocolate can only be facilitated by the first mouse. After some hesitation (that we still refuse to call moral thinking), the first mouse invariably chooses the second door to help the fellow mouse, and they go to eat the chocolate together.

The liberator mouse displays empathy. It also shares its own assured food supply. Subsequently, the mouse acquires an ally, so this decision is also profitable.

I also recall the story of John Jay O'Connor, late husband of Sandra Day O'Connor, the first female associate justice of the U.S. Supreme Court. While living in a care facility due to his progressing Alzheimer's disease, he developed a relationship with another woman at the facility. Surprisingly, it was reported that his wife was happy with the comfort he had found, an empathetic acknowledgment that patients with Alzheimer's disease sometimes develop new romantic relationships as their old ones fade from memory. It warms my heart that this couple enjoyed mutual emotional support, alongside a rare level of compassion and understanding from the former justice.

I reference these stories to reflect on some of our current moral compasses: humanity, empathy, and support of mental health. This fall, the campus of the University of North Carolina at Chapel Hill experienced multiple traumatic events, including the fatal shooting of a faculty advisor in the department of applied physical sciences. With Sigma Xi's headquarters right down the road in Research Triangle Park, the safety and well-being of our local members became one of our top concerns. That month, Sigma Xi scheduled a special emotional health workshop with our wellness partner, Happy. These recurring support sessions have been offered as a benefit to all members since 2021, when stress and loneliness were skyrocketing for many during the COVID-19 pandemic. We continue our dedication to supporting our members across the country—not just through grants, awards, and career development, but also through investing in their emotional well-being.

As scientists, we know we can learn a great deal from lab mice. However, all too often we only look at scientific data and experimental results. But if we look a little closer, a seemingly empathetic mouse may have something more to teach us (or remind us) about companionship and humanity.

Marija Strojnik

**Marija Strojnik**

# Shirley M. Tilghman Receives 2023 Sigma Xi Gold Key Award

Sigma Xi, The Scientific Research Honor Society is honored to announce that Shirley M. Tilghman, PhD, is the 2023 recipient of the Gold Key Award. As the Society's highest and most prestigious honor, the Gold Key Award is presented to a member who has made extraordinary contributions to their profession and has fostered critical innovations to enhance the health of the research enterprise, to cultivate integrity in research, or to promote the public understanding of science for the purpose of improving the human condition.

Dr. Tilghman will be recognized on November 11, 2023, in Long Beach, California, during the awards banquet at Sigma Xi's annual conference, the International Forum on Research Excellence (IFoRE).

"In addition to being a generational molecular biologist, Shirley Tilghman has forged one of the most respected careers in higher education," said Marija Strojnik, president of Sigma Xi. "Her accomplishments as an institutional leader, paired with her commitment to advancing STEM education and early career science, make her an exceptional recipient of Sigma Xi's highest honor."

A prominent molecular biologist, innovator, and educational leader, Dr. Tilghman is president emerita and professor of molecular biology and public affairs at Princeton University. A pioneer in research on genetics and genomics, Tilghman was a leading adviser to the National Institutes of Health (NIH) for the Human Genome Project. In addition to serving as Princeton's president from 2001 to 2013, she was named to Harvard University's principal fiduciary governing board, the Harvard Corporation, in 2015, where she still serves today.

A native of Toronto, Dr. Tilghman received her bachelor of science degree from Queen's University in Kingston, Ontario, in 1968. After two years of secondary school teaching in Sierra Leone, she earned her PhD in biochemistry from Temple University in Philadelphia. She did postdoctoral work at the NIH and contributed to many scientific breakthroughs as an independent investigator at the Institute for Cancer Research in Philadelphia. In 1986, she began her career at Princeton as the Howard A. Prior Professor of the Life Sciences. Over the next 15 years, she held many additional council and leadership positions at Princeton before being named president in 2001. Tilghman's exceptional contributions to science have earned her many awards, including the 2002 L'Oréal-UNESCO for Women in Science Award, the 2003 Lifetime Achievement Award from the Society for Developmental Biology, and the 2007 Genetics Society of America Medal.

In addition to her reputation as a distinguished scientist and researcher, Tilghman has been a nationally recognized leader and advocate throughout her career on behalf of women and young scientists. She has chaired organizations and authored recent publications focused on educational reform, the importance of diversity, equity, and inclusion in science, and promoting efforts to make the early careers of young scientists as meaningful and productive as possible.

The symbolism of the Gold Key Award pays homage to the early days of Sigma Xi (late 1800s to early 1900s), when induction into the Society was often accompanied by the presentation of a small gold key. The key was routinely attached as a charm to a bracelet or chain that held a pocket watch, which was the style of the day, and represented pride in the science or engineering accomplishments of the holder. Previous recipients of the award include Bruce Alberts, Shirley M. Malcom, Walter E. Massey, Gordon E. Moore, and Norman R. Augustine.

# Session Spotlights: IFoRE '23

IFoRE '23 will include a packed agenda with scientific thought leaders, award winners, and compelling session themes including research ethics, science policy, climate change, artificial intelligence, nanotechnology, genome editing, science communication, grant writing for students, and more! Visit **experienceIFoRE.org/agenda** to view the full conference agenda.

**Florida's Ecological Crises and How They May Inform Our Future**
James Sullivan
Florida Atlantic University

**Teaching Ethics in AI: A Practical Workshop for Educators**
Richard Whittington
Tuskegee University

**Our Future in Science: A STEM Education Model from Young People at the Intersection of Science and Social Justice**
Jylana Sheats
Aspen Institute

**Shifting Demographics in STEM Fields Through Community College Research Programs**
Jackie Swanik
Wake Technical Community College

# FACES of GIAR: Abhinav Sur

**Grant:** $1,000 in Spring 2018
**Education level at time of the grant:** PhD student

**Project Description:** The main goal of my project was to understand the potential genetic regulatory modules and differentiation trajectories underlying the diversification of cell types during embryogenesis in the annelid *Capitella teleta*. For that purpose, I captured single cells from *Capitella* larval stages and sequenced them to generate a single cell atlas of all genes expressed per cell in the whole larval body plan at two developmental stages. Our whole-organism scRNA-seq analysis generated comprehensive insights into metazoan cell-type evolution and tissue-specific genome-wide regulatory networks. This was one of the first attempts using such a systems-biology approach to answer developmental biology questions in the light of evolution.

The Sigma Xi grant was highly instrumental in enabling me to perform such high-throughput experiments, which are generally quite expensive. I used the grant money to perform the actual microfluidic capture of single cells and to sequence the single-cell transcriptomes.

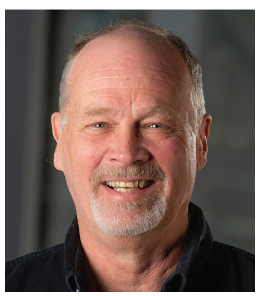
**How did the grant process or the project itself influence you as a scientist/researcher?**
The grant process and this project in particular greatly enhanced my motivation to become a scientist. For a long time, I'd had ambitions of using single-cell omics to answer evolutionary developmental biology questions; however, I was discouraged by the lack of funding and facilities at my university. The Sigma Xi grant was a huge push for me to accumulate funding from various sources to make this project possible.

**Where are you now?**
Right now, I am a postdoctoral research scholar at the National Institutes of Health, where I am using single-cell omics approaches to uncover cell-fate specification and to differentiate on during zebrafish development.

# Congratulations to Sigma Xi's 2023 Award Winners

Sigma Xi, The Scientific Research Honor Society is proud to announce its 2023 Award Winners. Presented annually by the Society's Prizes and Awards program, the awards recognize exemplary achievement in science and engineering. Recipients are presented with the awards at the International Forum on Research Excellence (IFoRE), where most will be plenary speakers. This year's conference will be held November 10–12, 2023, in Long Beach, California. More information on each recipient can be found at **experienceIFoRE.org/award-winners**.

*John P. McGovern Science and Society Award*



Ken Miller, PhD
Brown University

*Young Investigator Award*

Maryam Naghibolhosseini, PhD
Michigan State University

*William Procter Prize for Scientific Achievement*

John A. Rogers, PhD
Northwestern University

*Walston Chubb Award for Innovation*

Xin Zhang, PhD
Boston University

*Evan Ferguson Award for Service to the Society*

Malgosia Wilk, PhD
University of Texas at Arlington

# Announcing the 2023 Cohort of Sigma Xi Fellows

Sigma Xi is proud to announce the 2023 cohort of Sigma Xi Fellows. They will be recognized during the second annual International Forum on Research Excellence (IFoRE) taking place November 10–12, 2023, in Long Beach, California.

The Fellow of Sigma Xi distinction is awarded on a competitive basis to members who have been recognized by their peers. Fellows must be an active (dues-paying) full member for the past 10 years continuously, or a life member, with distinguished service to Sigma Xi and outstanding contributions to the scientific enterprise. Learn more about the 2023 Fellows and how to nominate members for future cohorts by visiting **sigmaxi.org/fellows**.

**David Allison**
Indiana University

**David Flannigan**
University of Minnesota

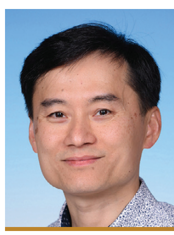
**Philip Wyatt**
University of California, Santa Barbara

**Diane Birt**
Iowa State University

**Digvir Jayas**
University of Manitoba

**Charles Rice**
Kansas State University

**Norman Augustine**
Princeton University

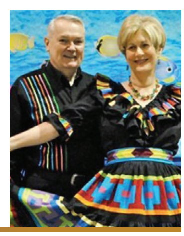


**Gary Shueng Han Chan**
Hong Kong University of Science and Technology

**Robert Youker**
Western Carolina University

**Kimberly Carlson**
University of Nebraska at Kearney

**Robert Horton**
University of California, Berkeley



**Akhlesh Lakhtakia**
Pennsylvania State University

**Frank Abrams**
North Carolina State University

**Liovando Marciano da Costa**
Membership-at-Large

**Stan White**
Orange County, California

**Shekhar Bhansali**
Florida International University

**Jonathan Clark**
Weber State University

**Michael Madden**
University of North Carolina at Chapel Hill